AEROSPACE INFORMATION REPORT

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A Guideline for Application of High-Density Fiber Optic Interconnects to Aerospace Platforms

RATIONALE

No further development of products for inclusion in this document are expected.

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FOREWORD

This document details various aspects of a Generation II high-density fiber optic interconnect system and related interface and installation hardware concepts for aircraft applications. The currently utilized Generation I fiber optic interconnect hardware, represents an extension or duplication of existing aircraft electrical cabling and connector technology to fiber optic media. It is therefore desirable to consider at the outset guidelines for an advanced high density interconnect system based on emerging technology concepts so that avionics interconnect systems can accommodate growth as the technology matures. This high-density interconnect will represent a revolutionary advance in interconnect systems based on optical fiber's unique performance characteristics. The concept should be compatible with all advanced aerospace system concepts including "fly-by-light", broadband multimedia networks such as passenger entertainment systems, advanced avionics computer interconnects (e.g. optical backplanes) and "smart structures". The vision is to attain a "mobile vehicle information distribution system" analogous to the "premises distribution systems" provided for buildings where all elements of a fiber optic interconnect are designed for compatibility and interchangeability.

This guideline addresses industry and government concerns with the affordability of first generation of interconnect hardware in order to provide solutions for improved second-generation hardware. This second-generation hardware should take into account advanced commercial network and "fly-by-light" systems implementation as well as recent technology advances by the commercial photonics industry. It is proposed that existing and planned industry wide consortia and working groups be used to provide input for this interconnect system for future military and aerospace applications since expertise from many disciplines and diverse organizations is required to arrive at workable solutions. It is also proposed that the automotive community participate in this effort to gain the economy-of-scale which can be achieved by possible dual-use aerospace/automotive application. Contributions and suggestions have been supplied by attendees of the AS-3C meetings held from October 1992 through April 1999.

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1. SCOPE:

This SAE Aerospace Information Report (AIR5271) covers the basic attributes of a second-generation robust, reliable high-density fiber optic interconnect system for aerospace applications. The intent is to take advantage of recent commercial developments in materials, components and manufacturing methods to develop rugged high-density fiber optic interconnects optimized for aerospace and automotive applications, which can accommodate a variety of optical fiber waveguide types. These waveguide types include single mode and multi-mode glass/glass fibers and waveguides, plastic clad silica fibers and waveguides, and all polymer fibers and waveguides. This second generation interconnect system should represent a dramatic improvement over first generation. The cable should be extremely robust eliminating any concerns over cable damage or fiber breakage in an aerospace environment.

A high-density fiber optic interconnect system provides the physical medium for optical data and control communication in aerospace vehicles. As such, it consists of the cables and harnesses, connectors, splices, backplane interfaces, transceivers, fiber optic couplers, and includes test and maintenance concepts for these items. Also included are manufacturing, installation and repair tools, processes and training programs. The high-density format should provide for both redundant serial data transmission or parallel data transfer by providing a scaleable fiber count. Connectors should provide an extremely small footprint, with low mass connector shells and array inserts, and accommodate both single and multi-mode fibers. Fiber spacing and cladding diameter should be standardized and coatings utilized to guarantee long term reliability. The cable connector interface shall be optimized to preclude damage during installation and/or maintenance actions as well as ease of termination. All elements of the cable plant should be compatible including splices and couplers with minimum weight, volume and footprint. This optimized cable plant shall serve as an integrated information distribution system capable of transferring all information on military and commercial aircraft with dramatic improvements in affordability, reliability, fault tolerance, EMI/EMP immunity and safety. Utilization of this cable plant will improve aircraft performance and fuel economy, providing operational cost effectiveness while reducing new aircraft certification costs.

2. AVAILABLE REFERENCE DOCUMENTS:

The following documents represent the current database for application of interconnects and related components to aerospace platforms:

MIL-STD-1678A	Fiber Optic Test Methods and Instrumentation
MIL-C-38999	Connector, Electrical Circular, Miniature; Specification for
MIL-C-83723	Connector, Electrical Rectangular; Specification for
MIL-E-5400T	Electrical Equipment, Aerospace General; Specification for
MIL STD 883	Microcircuits; Specification for
MIL-STD-1344	Test Methods for Electrical Connectors
MIL-STD-202	Test methods for Electrical and Electronic Component Parts
MIL-I-1760	Aircraft/Stores Electrical Interconnection System
MIL-C-83522	General Specification for Single Terminus Fiber optic Connectors
MIL-C-85045	General Specification for Fiber Optic Cable-Shipboard
MIL-F-49291	General Specification for Optical Fiber

2. (Continued):

MIL-T-29504	General Specification for Removable Fiber Optic Termini
MIL-STD-461	Requirements for the Control of Electro-magnetic Interference Emissions and Susceptibility
MIL-STD-462	Measurement of Electro-magnetic Interference Characteristics
MIL-W-5088	Wiring, Aerospace Vehicle
AS1773	Fiber Optics Mechanization of an Aircraft Linear Time Division Command/Response Multiplexed Data Bus
ARP5061	Guidelines for Testing of Aerospace Fiber Optic Inter-Connection Systems
ARINC 404-A	Air Transport Equipment Cases and Racking
ARINC 600-10	Air Transport Avionics Equipment Interfaces
ARINC Project Paper 628	Cabin Equipment Interfaces (CEI) Part 6 Fiber Optic Cable Assembly General Specification
ARINC 629P1-4	Multi-Transmitter Data Bus, Part 1, Technical Description
ARINC 629P2	Multi-Transmitter Data Bus, Part 2, Application Guide
ARINC 636	Onboard Local Area Network (OLAN)
ARINC 659	Backplane Data Bus
BELLCORE GR-326-CORE	Generic Requirements for Single-Mode Optical Fiber Connectors
DIN 47256	General Specification for Single Terminus Fiber Optic Connectors
RTCA DO-160C	Environmental Conditions and Test Procedures for Airborne Equipment
TIA/EIA-455-XX series	Fiber Optic Test procedures (FOTPs)
TIA/EIA-455-XX series	Optical Fiber System Test Procedures (OFSTPs)
TIA/EIA-604-X series	Fiber Optic Connector Inter-mateability Standards (FOCIS)

2.1 Sources for Reference Documents:

Reference Documents or additional information concerning reference documents can be obtained from the following sources[1]:

Aeronautical Radio Inc. (ARINC, USA, 1-410-266-4110)
HTTP://WWW.ARINC.COM/Ind_Govt_Srv/Characteristics/

Defense Supply Center (Dept. Of Defense, DSCC, USA, Art Hudson, 1-614-692-0657) HTTP://WWW.DSCC.DLA.MIL

Institute of Electrical and Electronic Engineers (IEEE, USA 1-908-981-0060)
HTTP://WWW.IEEE.ORG/

International Electro-technical Commission IEC, Switzerland +41-22-919-0211
HTTP://WWW.IEC.CH/

Radio Technical Commission for Aeronautics (RTCA), USA, 1-202-682-0266

Society of Automotive Engineers (SAE, USA, 1-412-776-4841, HTTP://WWW.SAE.ORG

1 Horwitz, Page 9

2.1 (Continued):

Telecommunications Industry Association (TIA, USA, 1-703-907-7700)
HTTP://WWW.TIAONLINE.ORG/

2.2 Definitions:

FIBER OPTIC CABLE CONDUIT. A rigid or semi-rigid tube within which the signal carrying media may be placed. It also serves the function of an external strength member to provide crush and abrasion resistance.

FIBER OPTIC RIBBON. An unprotected assembly of optical fibers arranged side by side in a flat configuration and held together by an adhesive or adhesive tape.

FIBER OPTIC RIBBON CABLE: A ruggedized stand alone assembly of two or more optical fibers arranged side by side in a flat configuration. The assembly may also provide mechanical strength for the fibers and a suitable protective coating to cover the buffered fibers for environmental protection and to maintain the subassembly configuration. The assembly shall be fabricated to meet optical, mechanical and environmental specifications.

FIBER OPTIC RIBBON CABLE BREAKOUT. An arrangement to physically and optically separate a particular information channel from all or several of the individual information channels contained in a fiber optical ribbon cable for the purpose of branching to another physical location. The individual fiber channel(s) to be separated shall detach cleanly from the ribbon matrix or adhesion materials without residue adhering to the separated fiber and a suitable means must be provided to maintain the physical durability and long term reliability of the cable at this detachment point.

HIGH-DENSITY FIBER OPTIC CABLE CONNECTOR. A quick disconnect mechanical assembly to physically constrain and position optical fibers in a fiber optic cable for the purpose of repeatedly and optimally transferring the optical signals in the fiber optic connector to an adjacent assembly which contains the following: (a) another fiber optic cable, (b) an array of optical sources, (c) an optical coupler, (d) an array of optical detectors, (e) and optical transceiver, (f) an optical switch or (g) an optical sensing device. The connector shall be fabricated to meet optical, mechanical, and environmental specifications.

FIBER OPTIC RIBBON CABLE SPLICE. A mechanical assembly to physically constrain and position optical fibers in a fiber optic cable. The assembly makes a permanent or temporary connection to transfer the optical signals in the fiber optic connector to an adjacent assembly containing another fiber optic cable, an array of optical sources, an optical coupler, or an array of optical detectors. The splice shall be fabricated to meet optical, mechanical, and environmental specifications.

FIBER OPTIC RIBBON CLEAVING TOOL: A mechanical or electro-mechanical device to simultaneously create physical break in all the fibers contained in a fiber optic ribbon cable which results in a flat surface on both facets on the severed optical fiber with minimal mechanical damage to the optical fiber. The flatness of the fiber surfaces and surface quality shall be specified to minimize optical loss.

2.2 (Continued):

OPTICAL BACKPLANE INTERCONNECT: A rigid stand-alone assembly consisting of optical waveguides, optical waveguide connectors and optical couplers that provides optical information transfer between standard electronic modules. This assembly provides structural support for the modules through a suitable connector interface as well as environmental and mechanical protection for the waveguides.

OPTICAL COUPLER. A component or device to provide optical power extraction from an input fiber or plurality of input fibers to a plurality of output optical fibers.

2.3 First Generation Fiber Optic Interconnect Constraints:

High-density fiber optic interconnects for aerospace applications offer the potential to simplify the harness complexity, reduce weight, simplify installation and reduce the maintenance. Additional benefits include operation in a high electromagnetic environment, improved cost effectiveness, increased aircraft performance and fuel economy, improved system performance capabilities, and reduced new aircraft certification costs. The multi-mode optical interconnects installed on aircraft to date have fundamentally been patterned on existing electrical cabling, connectors and harness concepts as well as currently utilized installation, test and maintenance procedures associated with electrical wiring. While this first generation hardware has been successfully implemented in several military and commercial aircraft, the extensive use once projected has not yet occurred because of issues related to cost, and ease of installation, test, and maintenance. In the commercial telecommunications industry, optical fiber high-density cable technology is receiving widespread use and provides compact cables providing a large number of fibers. This technology offers the benefits of low cost, mass termination and ease of installation. Complementary electro-optic component technology is also being developed to reduce the cost of commercial optical interconnects. This fiber optic high-density cable technology is also to provide a more cost effective second generation interconnect system for aerospace applications with projected widespread use of optical interconnects. This hardware is optimized around the unique properties of optical fiber rather than being an extension of electrical wiring and shall also provide increased long term reliability through cost effective built-in-test and affordable redundancy. The use of single mode fiber for aerospace applications is also optimized with a high-density cabling approach and is compatible with multi-mode fiber approaches.

2.4 System Requirements:

Operating Environmental Conditions:

Components of the cable plant shall not suffer damage, deterioration or degradation of performance, when subjected to any environment or natural combination of environments specified below:

Altitude: Sea Level to 70,000 feet with a maximum climb rate of 90,000 feet per minute.
Temperature Range: Dependent on actual and projected operational environment:

Class A: -40 to + 85 °C continuous, -55 to +125 °C for 5 minutes
Class B: -55 to + 125 °C continuous
Class C: -55 to 150 °C continuous, -65 to ≥200 °C for 5 minutes.

Humidity: Operating and non-operating conditions of 0 to 100 percent, including condensation in and on components where applicable.

Sand and Dust: Operating and non-operating conditions during and after exposure to sand and dust particles as encountered in dessert areas.

Fungus: Operating and non-operating conditions during and after infinite fungus growth as encountered in tropical regions.

Salt Fog Atmosphere: Operating and non-operating conditions during and after exposure to a salt/ sea environment as encountered in carrier service.

Shock and Vibration: Requirements for shock, sinusoidal and random vibration will be Established for survival in the severest flight test application.

Acoustic Noise Susceptibility: Requirements for acoustic noise susceptibility will be established for survival in the severest flight test application.

Electromagnetic Radiation: Per MIL-STD 461/462

2.5 Fiber Optic High-Density Cable Plant Benefits:

An optimized fiber optic high-density cable plant for both single and multi-mode fiber shall provide the following benefits:

TABLE 1

BENEFIT	METHOD OF ATTAINMENT
Operation in a High Intensity Electromagnetic Environment	Cable Plant Qualification to Aerospace Environmental Specification
Improved Cost Effectiveness	Greater Commonality, Built-in-Test, Parts Reduction, Low Cost Redundancy, Greater Reliance on Commercial Parts, Ease of Installation, Batch Fabrication
Increased Aircraft Performance and Fuel Economy	Weight Reduction
Improved System Performance	Growth Margin through Spare Fibers, Greater Availability through Redundancy, Fault Tolerance and Built -In-Test (BIT)
Reduced Certification Costs	Meet Aircraft EMI Requirement at the Box Level vice the Platform Level

It is the intent of this document to detail the main characteristics for a high-density cable interconnect system for aerospace applications which must be detailed in future standards and specifications.[2]

3. ADVANCED INTERCONNECT/HARNESS REQUIREMENTS:

The component requirements in this document are derived from the following sources:

1. Information on new systems needs and performance information on similar systems previously in actual use
2. Applicable portions of military specifications
3. Applicable portions of commercial specifications
4. Data from military and commercial technology demonstration programs.
5. Available or developmental commercial component and hardware technology

Formulating requirements derived from the above sources will permit qualification of a high-density fiber optic interconnect to provide reduced life cycle cost and technology transparency.

[2] Weaver et al., Sections 1-1, 1-2, 2-2, 2-8

4. EMERGING TECHNOLOGY TRENDS:

The telecommunications and CATV industries are striving to enhance service to subscribers. A convergence of these industries is taking place. This is driven by the emergence of high definition digital TV and digital video transmission over the internet. This convergence is driving bandwidth requirements for both “fiber-to-the-home” and “fiber-to-the desk”. The competitive pricing of both wireless and satellite services are driving affordability of fiber optic components for using fiber for the “last mile”. To increase bandwidth, wavelength division multiplexing (WDM) and sub-carrier multiplexing (SCM) technology are being pursued by the commercial sector. High-density cable and connector concepts are being rapidly advanced and a new family of lasers, modulators, couplers, filters, switches and detectors are emerging from the research laboratories.

Future incorporation of a fiber optic interconnect system on military platforms (e.g. aircraft) will permit the multiplexing of different information types/formats on a single optical fiber. When digital data transmission fiber is passing through a region of the aircraft that requires analog/RF communications signals to the core processor, it may be reasonable to use a different wavelength than the digital data and organize the new wavelength bandpass into a Frequency Division Multiplexed (FDM) optical channel. The process of modulating the optical light carrier with another frequency carrier is called Sub-Carrier Multiplexing. The FDM information on another wavelength can now pass down the optical fiber while not interfering with the original digital information. At the analog/RF pick-off point, a wavelength selective optical filter and/or detector is used to convert the RF information back into electrical. No reason exists to preclude utilization of two or more of these digital fibers for broadband ring or LAN networks, operating on different optical wavelengths. The advantage provided is information rate growth and a corresponding platform capability improvement through multiplexed photonics. With thoughtful initial design, which includes redundancy, fault tolerance and built-in-test (BIT), a scaleable cable plant can be designed for the life of the airframe so that no optical cable upgrades would ever be required.

Emerging technology trends, which require high-density fiber optic interconnects are resulting from many diverse efforts. One example effort is the military sponsored True Time Delay (TTD) development for phased array antennas. These efforts are expanding the spectral performance limits of existing photonics interconnect elements; including: external optical modulators, photonic selective time delays, wide band photodetectors, lower Relative Intrinsic Noise (RIN) laser techniques and optical switching. Another characteristic of lasers is the spectral line width. The higher line widths the greater phase noise placed on the signal near DC. Fortunately methods to increase optical power tend to improve the spectral line width and RIN. The majority of these devices are being developed for control of Phased Array antennas and Analog/RF links through fiber optic interconnects, possibly via WDM on other normal interface optical cables. As photonics develops in the military platforms it will be necessary for growth to be accomplished without constantly laying new optical fiber cables.

4. (Continued):

Fly-by-light demonstrations are advancing through continuing flight tests and there is an increasing requirement for diagnostics and health monitoring of structural, propulsion, and avionics systems on all aerospace platforms. Antenna Systems are being incorporated into the skins of aircraft and structural elements are being monitored and controlled by embedded sensors and actuators. “Fly-by-light”, “smart skins” and “smart structures” will require efficient data transfer in a severe environment and must be subjected to the same environmental stress as the airframe. High-density optical cables and connectors can be exploited for this purpose. The interconnect can be embedded into structures, laminated on the surface of structures and/or routed in a conventional means to transfer data and serve as an optical sensing mechanism.

4.1 Optical Fibers for High-Density Cables:

Conventional optical cables consist of a single fiber or fibers that are laid up with suitable longitudinal strength members in a bundle connector. These fibers and strength members are configured in a bundle configuration over which is placed a protective sheath. The sheathing can be helical wrapped or extruded and a final cable jacket is placed over the assembly to form a cable. An alternative option for assembling optical fibers is to configure the fibers in a side by side configuration to form a flat ribbon which can then be utilized to form various cable configurations. Figure 1 shows a cross section of such a fiber optic ribbon wherein the unprotected fibers are held in position by an adhesive.

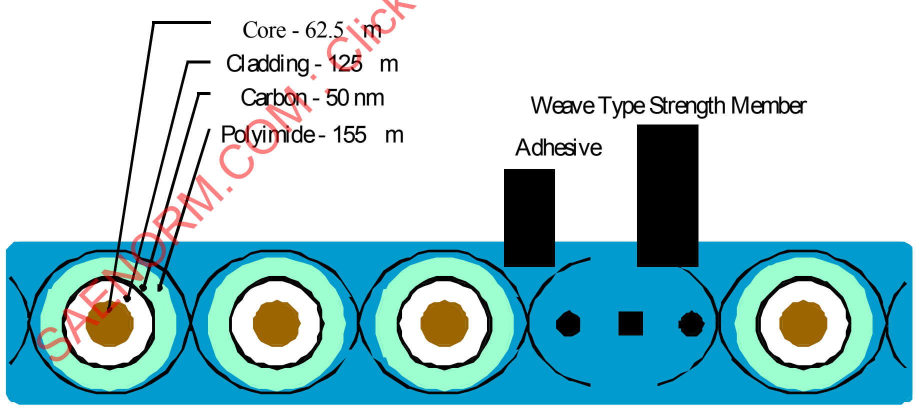

FIGURE 1 - Cross Section of a Fiber Optic Ribbon

4.1.1 Glass Fibers: Driven by the long distance telecommunications market, the glass optical fiber industry has produced low loss, low dispersion single mode glass fiber with loss minima in the 1.3 micrometer and 1.5 micrometer wavelength windows. Further stimulated by the Community Antenna Television CATV market (i.e. cable TV), National Information Infrastructure developments, and the market for local area networks (LANS), the industry is emphasizing development of multi-mode glass fiber with more emphasis on affordable cost. These multi-mode systems operate in the .85 micrometer, 1.3 micrometer, and 1.5 micrometer loss windows. The fiber industry has now recognized the advantages of applying hermetic coatings to fibers long term reliability and some manufacturers now provide such coatings in their product inventory.

Hermetically coated single mode and multi-mode glass fibers are now commercially available for aerospace applications. In the past, the unavailability of MIL-SPEC lasers, single mode connectors and reliable couplers has also been a problem, which has prevented the introduction of single mode fibers into aerospace applications. Some sensor applications will require single mode fiber optic technology on aerospace platforms. Broadband networks will require laser sources to meet the bandwidth requirements of next generation video and sensor data transmission. It is therefore imperative that next generation aerospace cable plants incorporate the requirement for both single mode and multi-mode technology. The broad telecommunication market will help to lower costs associated with single mode technology while the Local Area Network (LAN) and fiber-to-the desk market should help reduce the cost of multi-mode fiber.

Commercial single mode and multi-mode fibers have adopted de facto standards for fiber core and cladding. The most common commercial multi-mode core cladding diameters are 62.5/125 μm and 50/125 μm. Likewise single mode fibers have also adopted a 125 μm cladding dimension. The first generation aerospace cables have adopted de facto standard of 100/140 μm and 200/280 μm and utilize a polyimide or silicone buffer to provide high temperature capability. Commercial fibers utilize an acrylate coating which cannot meet the higher temperature aerospace requirements.

A new family of commercial multi-mode fibers has been introduced by Corning with superior technology and profile control that provides performance previously available only with single mode fiber. The InfiniCor CL 1000 fiber is guaranteed for transmission distances up to 500 meters at 850 nm and up to 1000 meters at 1300 nm for gigabit Ethernet compliant systems. This is the first multi-mode fiber to eliminate the need for a mode-conditioning patch cord in the 1300 nm window and is specifically designed for laser-based systems. The fiber performance characteristics are based on actual laser bandwidth measurements. Typical applications are local area networks using 850 nm VCSELs. 980 nm CD lasers, and 1300 nm Fabry-Perot lasers. The fiber is designed to operate from -60 to +85 °C. [3]

[3] Corning Press Release of 23 Feb.'99 and related data sheets

4.1.2 Plastic Optical Fibers (POF): Plastic optical fibers are flexible and easy to terminate, they are usually large in diameter and durable, the cost to connect in a system is low and they can operate in the visible and infrared regions. Early development of step index POFs provided fibers mostly for lighting, illumination and display. A fraction of fibers were used for data communication. With the invention of high bandwidth PMMA (polymethyl methacrylate) based graded index POFs[4], they became suitable for communication and with the development of new perfluorinated graded index fibers [5]they can now operate in the infrared region. As the components such as opto-electronic devices and connectors for the POFs are becoming available, their penetration into the communication marketplace can be significant.

Typically step index fiber consists of a PMMA core with a fluorinated polymer cladding. The graded index fiber has a doped PMMA core with a PMMA based cladding. The newer perfluorinated graded index fiber has a doped core that diffuses to outside clad during the fabrication process. Boston Optical Fiber (BOF) Corp. is utilizing three methods to produce GIPOFs[6]: the interfacial gel polymerization (IGP) method and two diffusion techniques. All three methods use low molecular weight dopants to vary the refractive index of the core. All dopants decrease the glass transition temperature of the fiber core.

4.1.2.1 Optical Characteristics of POF: Optical attenuation of POF is measured[7] using a cut back method where the fiber is cut at a length of 2 to 5 m from the end. Ends of fiber are polished. Optical power through the fiber is then measured and the attenuation is calculated using the input and output powers per unit length. A typical attenuation result for a step index fiber is shown in Figure 2. A typical attenuation result for a graded index fiber (BOF) is shown in Figure 3.

A typical attenuation result reported[8] for a perfluorinated GIPOF was less than 100 dB/km at 650 to 1300 nm wavelengths and the lowest attenuation of 50 dB/km was observed at 1300nm.

Some of the optical properties, such as, optical attenuation, bandwidth, and numerical aperture (NA) are summarized in Table 2.

A typical bend radius POF can withstand is around 25 mm. Bending loss depends on the number of bends, bend radius, and fiber numerical aperture (NA).

4 Koike et al., p. 46
5 Yoshihara et al., p. 27
6 Illashenko and Berman, 1998
7 JIS C 6863 , 1990
8 Yoshihara et. al, p. 27

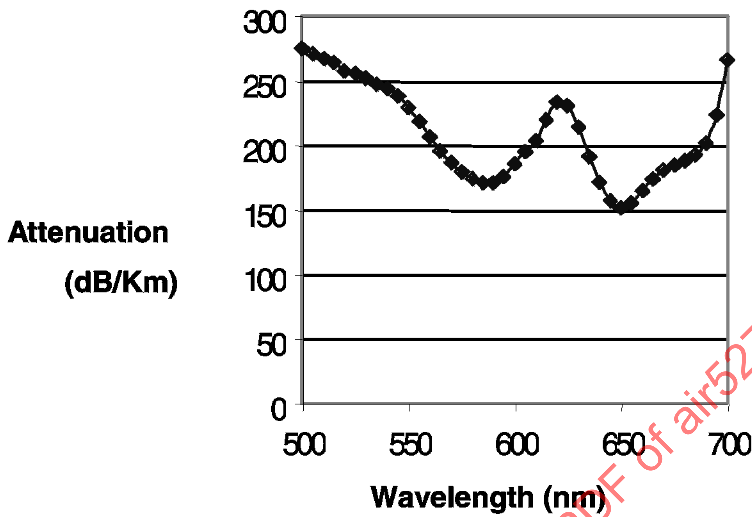

FIGURE 2 - Typical Attenuation Plot For A Step-Index POF

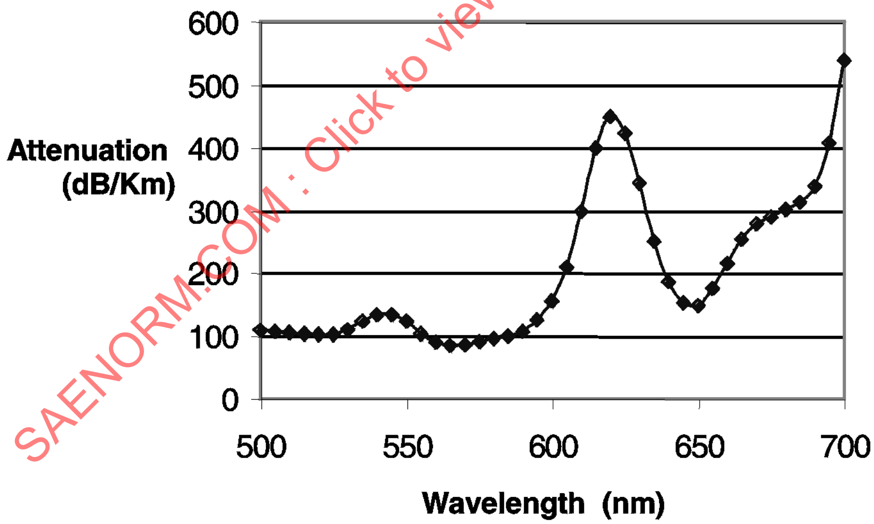

FIGURE 3 - Typical Attenuation For A Graded-Index POF

TABLE 2 - Optical Properties of Different POFs

Properties	SIPOF	GIPOF (PMMA)	GIPOF (Perfluorinated)
Attenuation (dB/km) @650 nm	140-150	150-180	<100 (650-1300 nm)
Bandwidth (MHz/100 m)	100-1000	1000-2500	3000-6000
Numerical Aperture	0.3-0.5	~0.2	~0.2

4.1.2.2 Mechanical Characteristics of POF: Typically tensile testing is done using a tensile tester. In this test, a finite length of fiber (25 to 50 cm) is wrapped around top and bottom capstans and the fiber is pulled in tension. Typically the yield force, breaking force, and elongation are recorded.

Typical breaking force for the SIPOF is around 9 kg with an elongation of nearly 100%, whereas for the graded index fibers the breaking force is lower due to additional dopants into the core.

When the SIPOFs are subjected to compressive loading, typical added attenuation was reported to be <0.2 dB for a 50 kg load [9].

When the fibers are subjected to different temperatures and humidities, SIPOFs and GIPOFs behave differently. Typically, the SIPOFs can withstand temperatures up to 85 °C without any change in attenuation for 1000 hours. As the fibers are exposed to humidity at 85 °C, the attenuation increased to nearly 3 dB/100 m.[10] In the case of GIPOFs, an attenuation increase of 10 dB/km was reported[11] when the fibers were exposed to 70 °C for 1000 hours. When the SIPOFs are exposed to room temperature water for nearly 3 months and later tensile tested at ambient conditions, the breaking force of the fiber dropped by ~15%.[12] POFs in general can withstand different harsh environments such as seawater, sodium hydroxide, engine oil and sulfuric acid.[13]

9 POF Data Book, Published by MRC Techno Research Inc. (1993).

10 Technical Bulletin, Toray Industries Inc.

11 Lucina Optical Fiber, Asahi Glass.

12 D Biswas, V. Ilyshenko and G. Hulse, p.44

13 Technical Bulletin, Toray Industries Inc.

4.1.2.2 (Continued):

Plastic Optical Fiber (POF) has the potential for significant improvement in termination complexity, interface robustness, and cable repairability over glass fiber and copper media. Current POF technology is limited by the base material polymethylmethacrylate (PMMA) which restricts the operating distance to 50 meters, the operating temperature to 85 °C, and the transmitter wavelength to 650 nm. New material development using Fluoropolymer Graded Index POF (FGIPOF) will improve the attenuation for wavelengths of 650 to 1300 nm allowing the use of gigabit 850 nm VCSELs and 980 nm ruggedized lasers. FGIPOF will increase the operating temperature range to (-55 to 150 °C) overcoming the temperature restrictions of aerospace applications. Distance and bandwidth capability will also increase providing a fiber link capable of greater than 1Gb/s over 100 m or 2.5 Gb/s over greater than 30 m.[14]

4.1.3 Hard Clad Silica (HCS) Fibers: A new family of fibers with a pure silica glass core and hard polymer (with proprietary composition) cladding is being considered for aerospace applications because of the inherent strength and ease of termination. These fibers are also receiving attention for local area networks in the commercial sector.[15,16]

4.1.4 Radiation Hardness: Past radiation hardened fiber based system designs have evolved from the requirements to survive nuclear weapons effects. Current system designs have focused on other environmental needs (i.e. nuclear power plants, nuclear waste management, and the natural space environment). These new adverse environmental requirements along with nuclear weapon survivability criteria have increased interest in the development of radiation hardened optical fibers and associated components. These new requirements have also increased the spectrum of survivability as well as the types of degradation. The most common fiber types that have been considered for space systems are large core (>100 µm), step index, multi-mode fibers for data transmission and polarization preserving single mode fibers for sensors.

The natural space environment, while less severe than the effects of nuclear weapons, is very important because of the wide variety of nuclear phenomena it encompasses. The principal concerns for fiber based systems in the space environment include total dose due to electrons and protons in the Van Allen Belts, solar flare particles and ionizing energetic ions (cosmic rays). Table 3 presents a summary of the most dominant radiation effects on elements of a fiber based system.[17]

14 Cirrilo and Steele
15 U.S. Patent 5,381,504
16 Novak et al.
17 Greenwell and Barnes, p.215, Table 1.

TABLE 3 - Most Dominant Radiation Effects On Elements of A Fiber Based System

Element of Fiber Optic System	Nuclear Radiation Type				
	Total Dose	Prompt Transient	Proton Fluence	Neutron Fluence	Charged Energetic Particles
Transmitter	Circuit Noise Increase	Circuit Upset/Burnout	Circuit Gain Decrease	Circuit Gain Decrease	Single Event Upset/Latchup
LED	Other Effects Dominate	Other Effects Dominate	Light Output Decrease	Light Output Decrease	Other Effects Dominate
Laser Diode	Other Effects Dominate	Other Effects Dominate	Threshold Current Increase	Threshold Current Increase,Quantum Effect Decrease	Other Effects Dominate
Coupler/ Connector	Attenuation Increase	Other Effects Dominate	Other Effects Dominate	Other Effects Dominate	Other Effects Dominate
Optical Fiber	Attenuation Increase	Increased Attenuation Luminescence	Attenuation Increase	Other Effects Dominate	Other Effects Dominate
Photodiode	Leakage Current Increase, Optical Responsivity De-Crease	Induced Photocurrent	Leakage Current Increase	Responsivity De-crease, Leakage Current Increase	Transient Photocurrent
Receiver	Circuit Noise Increase, Circuit Sensitivity Decrease	Circuit Upset/Burnout	Circuit Gain Decrease	Circuit Gain Decrease	Single Event Upset/Latchup

4.2 Optical Fiber Physical Properties:

In order to adequately specify and standardize on a fiber optic high density cable for aerospace applications, the following physical fiber characteristics must be specified as well as parameters for assuring uniformity from fiber to fiber.

- Fiber Core and Cladding Composition
- Fiber Core and Cladding Diameter
- Fiber Core/Cladding Concentricity
- Fiber Buffering Diameter
- Fiber Buffering/Cladding Concentricity
- Fiber Core Non-circularity
- Fiber Coating Material Composition
- Fiber Coating Diameter
- Fiber Core/Cladding/Buffering/Coating Concentricity
- Fiber Color Coding
- Buffered Fiber Flammability Resistance
- Resistance to Fluids
- Fiber Minimum Bend Radius
- Fiber Tensile Strength
- Fiber Temperature and Humidity Tolerance

4.3 Optical Properties of Fibers:

In order to adequately specify and standardize a high-density cable plant for aerospace applications, the following optical characteristics shall be specified as well as uniformity in optical properties from fiber to fiber.

- Fiber Numerical Aperture
- Fiber Index Profile
- Fiber Mode Field
- Fiber Operating Wavelength
- Fiber Attenuation vs. Wavelength
- Fiber Micro-bending Loss
- Fiber Bandwidth
- Fiber Modal Characteristics

4.3 (Continued):

- Fiber Polarization Characteristics
- Fiber Radiation Hardness
- Fiber Cutoff Wavelength
- Fiber Chromatic Dispersion

4.4 Fiber Optic Ribbon Cable Construction:

Ribbon fiber optic cable for aerospace applications can be categorized as: (1) encapsulated fiber optic ribbon cables and (2) Non-encapsulated fiber optic ribbon cables.

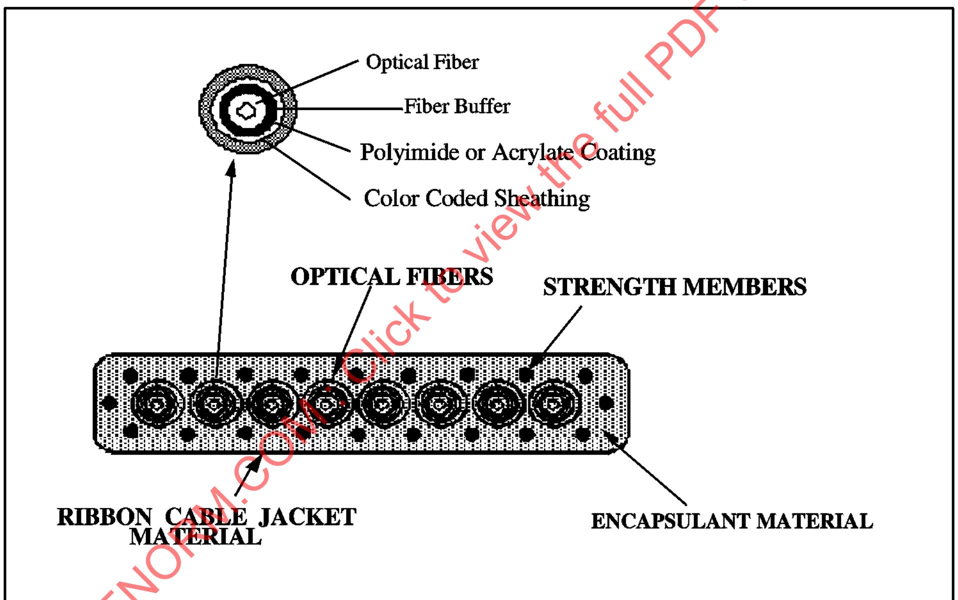

FIGURE 4 - Cross Section of an Encapsulated Fiber Optic Ribbon Cable

4.4.1 Encapsulated Fiber Optic Ribbon Cables: The encapsulated fiber optic ribbon cable utilizes a grid like structure wherein a fiber optic ribbon and a strengthening member are positioned and held in a composite structure in a manner to optimize the optical and physical properties of the cable. The strength members, which are embedded in a flexible encapsulant material are comprised of longitudinal or helically wound fibers of glass, Kevlar, or other suitable materials or comprised of a woven fiber fabric which surrounds the optical fibers. A suitable encapsulant material, such as an elastomer, is applied to a matrix of the optical fibers and strength members to seal the structure providing mechanical and environmental protection for the fibers and forms a flexible sheet. A further coating is applied over the encapsulant to provide scuff and abrasion resistance. Figure 4 depicts the cross section of a typical encapsulated fiber ribbon cable with a jacket to surround eight optical fibers and encapsulant. Figure 7 is a photo of an encapsulated fiber optic ribbon cable.

4.4.2 Non-Encapsulated Fiber Optic Ribbon Cables: A non-encapsulated fiber optic ribbon cable is similar in construction to currently utilized fiber optic cables. Individual optical fibers are retained in a side-by-side flat configuration through the application of a suitable adhesive material or use of an adhesive strip to form a fiber optic ribbon. This ribbon of optical fibers, held in place by the adhesive, is helically wrapped with a suitable material to provide mechanical and environmental protection to the adhesively joined fibers. Longitudinal strength members are placed over and under the wrapped ribbon fibers and a final tubular jacketing is applied to form a stand alone flat fiber optic ribbon cable. Figure 5 is a cross section of a non-encapsulated cable and Figure 6 is a photo of a cable with this type construction.

4.4.3 Fiber Optic Ribbon Cable Physical Properties: A next generation ribbon cable plant shall utilize an optimum ribbon cable construction for the particular application. The choice of cable construction and materials will impact many physical and optical properties including micro-bending sensitivity, splice ability, fiber stress corrosion, thermal stability, aging stability, ease of termination, breakout capability etc. Properties of cabling materials, which must be considered, include Young's modulus, melting point, adhesion, viscosity, etc. .

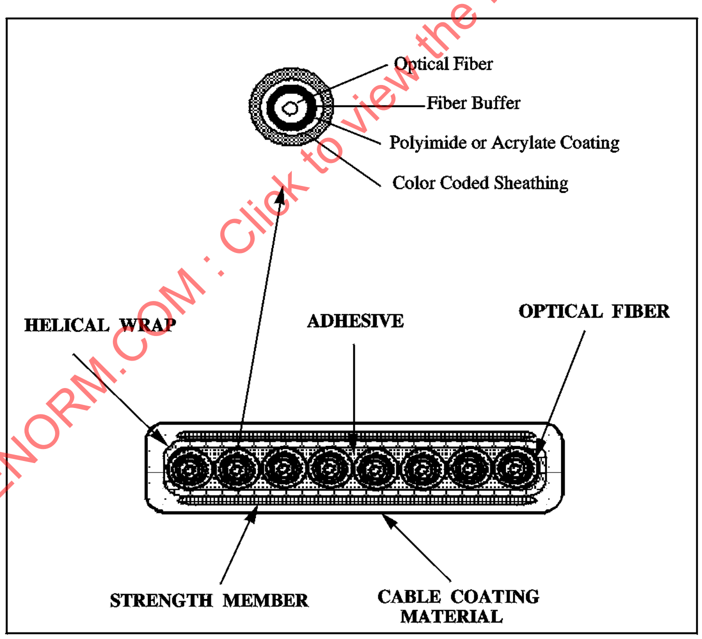

FIGURE 5 - Cross Section Of An Non-Encapsulated Fiber Optic Ribbon Cable

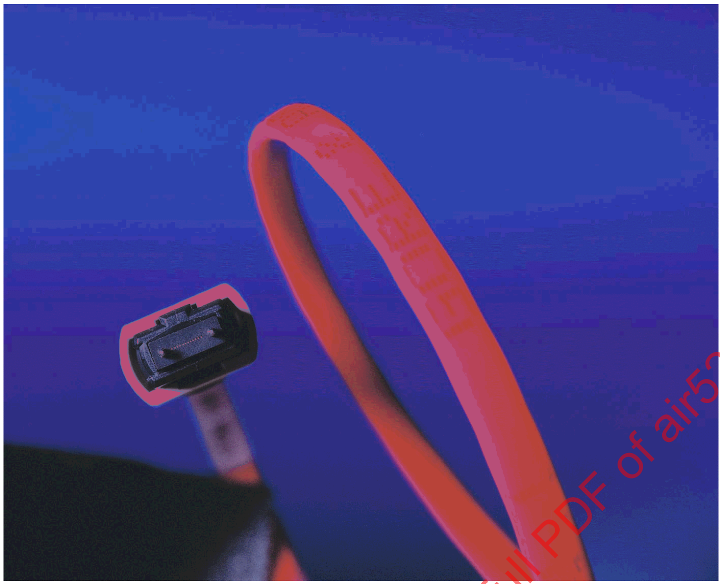

FIGURE 6 - A Non-Encapsulated Ribbon Cable With an MT Connector (Courtesy Gore Associates)

FIGURE 7 - An Encapsulated Fiber Optic Ribbon Cable With a Woven Strength Member From Patsi With Silicon V-Groove Connectors from Fotron Corp. (Courtesy Lockheed Sanders Corp.)

4.4.3 (Continued):

Below is a list of physical cable parameters and applicable documents, which detail the parameters which shall be specified to meet performance and environmental requirements for aerospace applications

- Cable Type
  - Encapsulated
  - Non-encapsulated
- Cable Strength Member
  - Woven
  - Longitudinal
  - Wrapped
- Number of Fibers in Cable
- Fiber Spacing in Cable
- Cable Geometry
- Cable Cross Section Dimensions
- Cable Tensile Strength
- Cable Cyclic Flexing
- Cable Bend Sensitivity
- Cable Torsion Resistance
- Cable Temperature Tolerance
- Cable Humidity Tolerance
- Cable Crush Resistance
- Minimum Cable Bend Radius
- Cable/Fiber Coating Colors
- Cable Aging Stability
- Cable Water Blocking
- Cable Breakout and Stripability
- Skew Properties
- Cable Fluid Resistance

4.4.4 Stacked Fiber Optic Ribbon Cables: Because of the flat nature of fiber optic ribbons, these ribbons can be stacked to form an organized two dimensional array of fibers. Ribbons shall be cabled in various configurations to achieve even higher packing density than a single ribbon cable. Figures 8 and 9 show isometric views of commercial circular stacked fiber optic ribbon cables. This organized, and indexed fiber cabling approach is analogous to the ribbon organized interconnect (ROI) utilized for electrical wiring on the Navy V-22 Osprey tilt rotor aircraft.

4.4.4 (Continued):

The stacked ribbon approach can also be utilized for an encapsulated ribbon to form a two dimensional cross section square or rectangular cable. In the case of encapsulated ribbons, the encapsulant must be used to encase the multi-ribbon stack including strength members in the fabrication process while in the non-encapsulated case; the individual ribbon cables may be contained in a common jacket to form a stacked ribbon cable. As with the flat ribbon cable, these cables provide the option for batch cleaving and polishing as well as cost effective termination concepts.

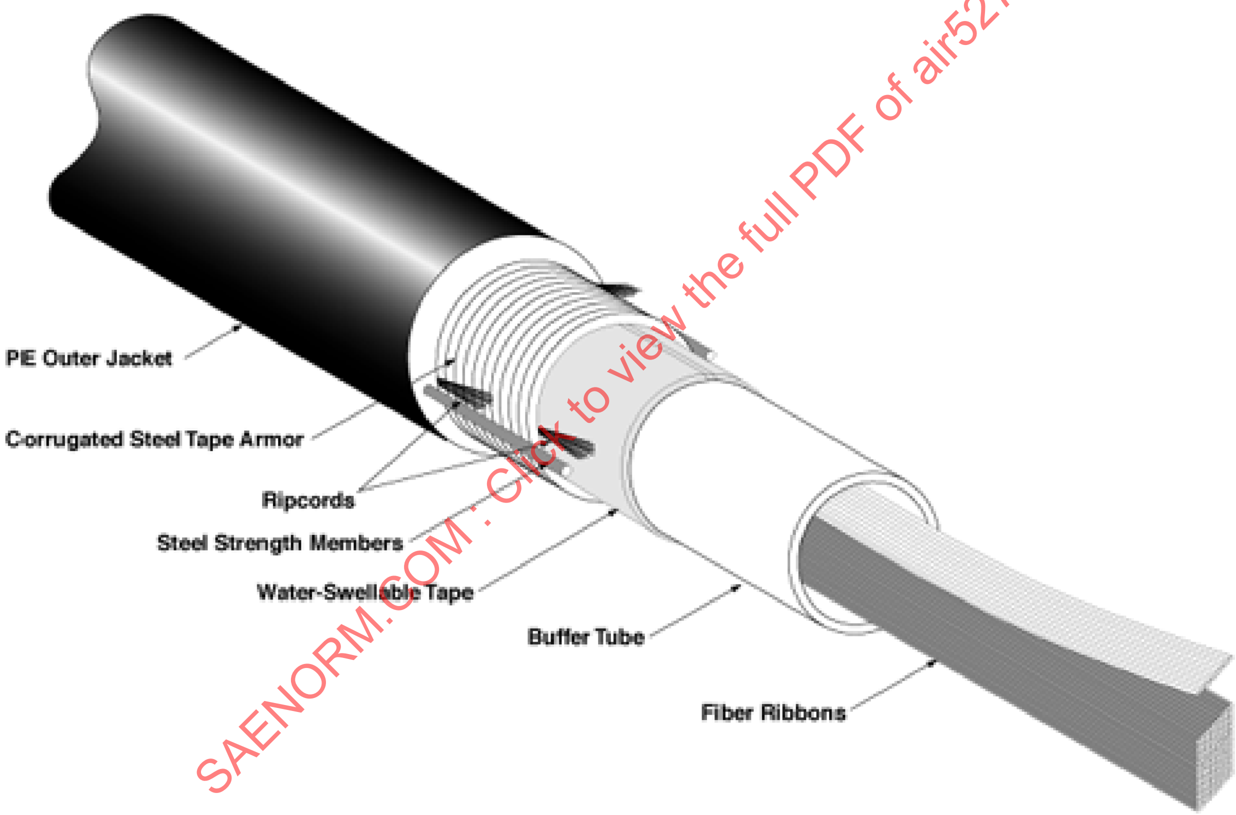

FIGURE 8 - An Armored Circular Stacked Fiber Optic Ribbon Cable[18]

[18] http://www.siecor.com/public/p-altosa.htm

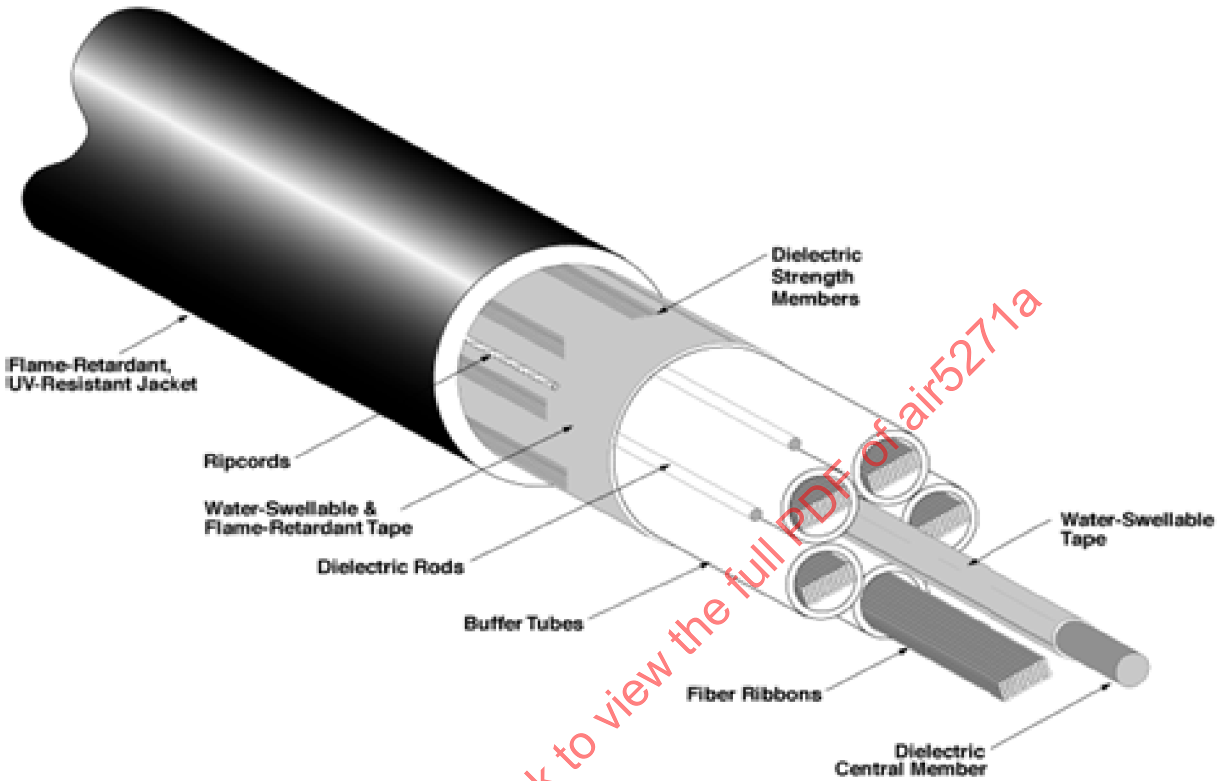

FIGURE 9 - A Commercial Stacked Ribbon Cable With Dielectric Strength Members[17]

4.4.5 Suggested Cable Test Procedures: Cables shall be tested in accordance with applicable EIA/TIA or equivalent MIL Standards to assure compliance with operational and environmental requirements. To perform testing, launch conditions shall be in accordance with applicable EIA/TIA and or MIL standards.

4.5 High Density Fiber Optic Termination Concepts:

The flat configuration of fiber optic ribbon permits the use of batch fabricated and grooved planar multi-fiber termini concepts. The termini can be batch fabricated by chemical etching, molding, electro-forming etc., to provide alignment of the individual fibers in a ribbon. The photo-lithographic definition and/or precision micro machining of these grooves provide very accurate dimensional tolerance. The commercial telecommunications industry has been exploring mass array terminations at low cost and high volume. These commercial termination concepts can be adapted to aerospace applications at a reasonable cost. Figure 10 is a cross section of a single crystal silicon chip in which a V-groove has been photographically defined and chemically etched along a preferred crystallographic plane. The V-grooves are etched to accommodate a specific fiber size and suitable alignment features may also be defined on the edges of the chip.

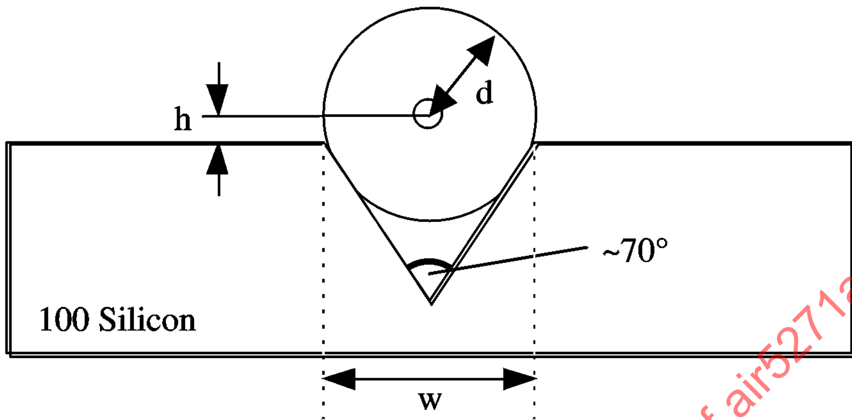

FIGURE 10 - Cross Section Of A Silicon V-Groove Etched In A Silicon Substrate

4.5 (Continued):

The fibers are laid into the V-groove after the cabling and coatings have been stripped from the fiber. Certain coatings such as polyimide may be retained on the fiber after placement in the groove. A mated silicon V-Groove chip shall be bonded over the fibers to form a registered pair with external alignment and registration grooves. This batch termini block shall be placed in a circular or rectangular backshell with a suitable retention, sealing and mating mechanism. To implement a lens into a silicon V-groove termini block, (1) an extended V-groove shall be etched in the silicon to place a graded index rod in front of the optical fiber to expand the optical beam or (2) another groove shall be etched to align a spherical lens in front of the optical fiber. Also micro-lens arrays fabricated as a monolithic window can be placed in front of the silicon alignment block to protect fiber surfaces and enhance optical performance. Figure 11 is a photomicrograph of an etched silicon substrate containing silicon v-grooves.[19]

To terminate stacked fiber ribbon cables silicon alignment blocks shall be stacked and bonded to provide registration of the fibers in a stacked fiber ribbon cable. Connectors utilizing silicon V-Groove multi-fiber termini are currently manufactured by Berg, AT&T, Fotron Corp. et. al. Figure 12 is a picture of a commercial connector that utilizes the silicon V-groove termination. A military version of this that utilizes the same V-groove termination concept is available for military systems.

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19 http://www.siecor.com/public/p-altosd.htm

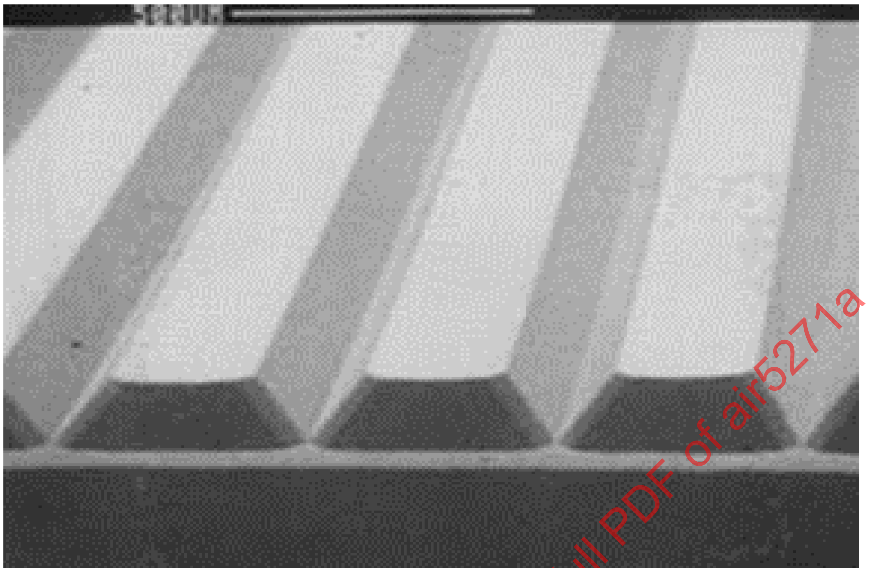


FIGURE 11 - A Photomicrograph of an Etched Silicon Substrate Containing Silicon V-Grooves

FIGURE 12 - A Silicon V-Groove Connector (Courtesy Berg Electronics)[20]

4.5 (Continued):

Another solution to the difficulties of fabricating a high-density optical connector is precision molding techniques. One example of such a multiple contact termination connector that is commercially available is the MT connector. The MT ferrule of Figure 13 is a multi-fiber termini that is commercially available in 4, 8, 12, and 16 density for a single connector. Additionally, stacks of five 16-fiber connectors are available creating an 80-fiber connector assembly.[21]

20 http://www.bergelect.com/product/optic/optic_mini.htm

21 Satake et al., p.997

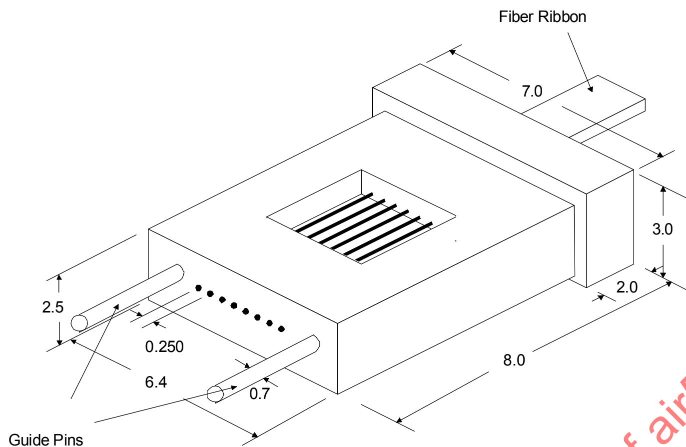
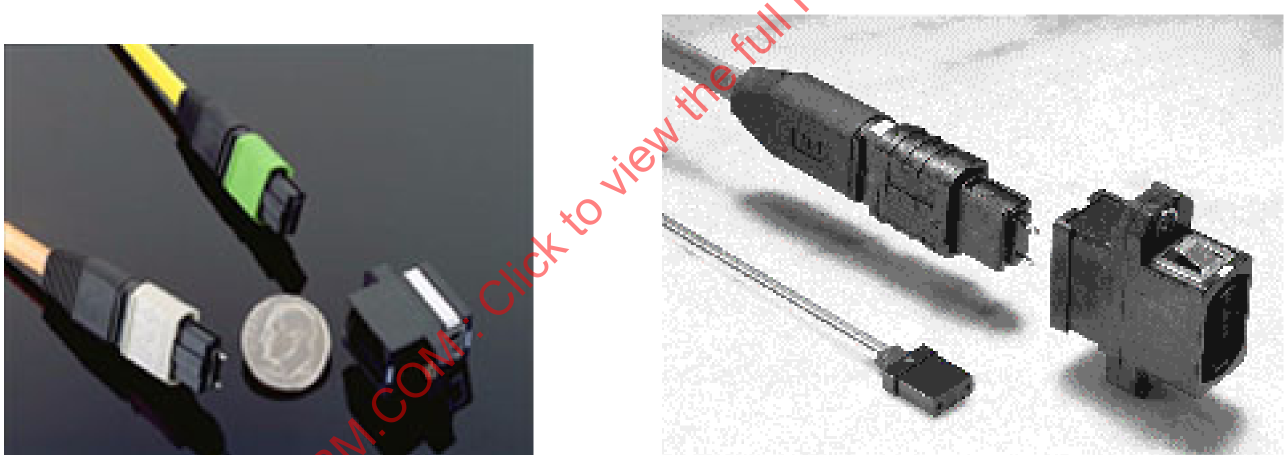


FIGURE 13 - A Molded MT Array Ferrule



(1) (2)

FIGURE 14 - A Molded Connector (Courtesy (1) USCONEC[22] and (2) Molex[23])

22 http://www.usconec.com/products/

23 http://www.molex.com/product/fiber/fomtcabl.html

4.5.1 Fiber Optic Termini Properties: The relevant properties of connector Termini that must be specified are listed below:

- High Density Interface Definition
  - Silicon V-Groove
  - Machined Ceramic Insert
  - Alignment Bearings
  - Hexagonal Packed arrays
  - Molded V-Grooves
  - Micro-lens arrays
- Alignment Mechanisms
  - Dowel Pin Spacing
- Fiber geometry and spacing
- Connector Optical Interface
  - Butt Joint Flatness
  - Angle polish specification
  - Spherical lens properties
  - Graded Index Rod lens properties
  - anti-reflection coatings
- Maximum optical Attenuation
- Reflectance

4.5.1.1 Multi-Fiber Array Ferrule Termination Procedures: The following termination procedure for the MT ferrule has been developed by USCONEC Corp. The termini and equipment for this termination is commercially available through document CD A01-003, Issue –2, of January 1998.[24]

Fiber Ribbon Preparation: . Mark the ribbon approximately 25 mm from the end.

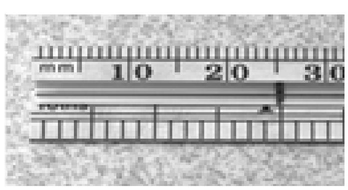


FIGURE 15 - Ribbon Preparation Procedure Step 1

Place the ribbon in a ribbon holder.

[24] http://www.usconec.com/MTPprocs.htm

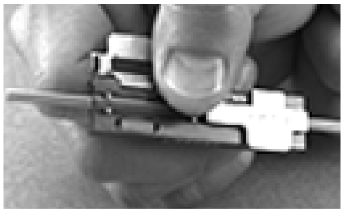


FIGURE 16 - Ribbon Preparation Procedure Step 2

4.5.1.1 (Continued):

Using a hot ribbon stripper, remove the ribbon material and the fiber coating.

FIGURE 17 - Ribbon Preparation Procedure Step 3

Clean the bare fiber strands with a lint-free wipe and alcohol to remove coating residue.

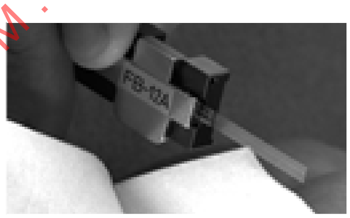


FIGURE 18 - Ribbon Preparation Procedure Step 4

Place the ribbon holder into a fiber-cleaving device and cut the fibers evenly at a length of 10 (±3) millimeters. Check for damaged or broken fibers. Note: A smooth, even cut will aid fiber insertion into the ferrule. Remove the ribbon from the holder. Slide a rubber ferrule boot onto the ribbon taking care not to break the bare fibers. The boot should be oriented so that the thicker half, which contains a small number, is closest to the bare fibers.

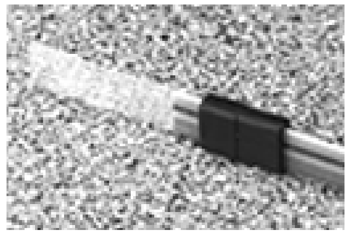


FIGURE 19 - Ribbon Preparation Procedure Step 5

4.5.1.1 (Continued):

Determine which edge of the ribbon is the #1 fiber. Typically, the #1 fiber has a black stripe on the ribbon or is the dark blue colored fiber in the ribbon matrix.

Obtain a ferrule and find the colored dot on the side.

FIGURE 20 - Ribbon Preparation Procedure Step 6

With the #1 fiber to the side of the ferrule marked with the colored dot, insert the fibers into the rear of the ferrule. Tilt the ribbon slightly while looking through the window of the ferrule, watch the fibers move along the guide grooves and gently insert them into the ferrule. The fibers should slide into the holes and pass smoothly through the ferrule end face, however, if any resistance is felt, back the fiber out slightly and try again, watching in the window to ensure all fibers are in the proper track. Any bending of a fiber signifies misalignment and will cause fiber breakage. After confirming the fibers fit into the ferrule, remove the ferrule from the ribbon. MT installation onto single-mode fiber requires EPO-TEK 353 ND (clear) Epoxy. Combine the main part (transparent; part A) to the catalyst part (amber: part B) with a ratio of 10 to 1 (A to B) by weight in a container. Mix and de-gas thoroughly. Cure time for this epoxy at 80 (± 5) degrees Celsius is 55 minutes. MT installation onto multi-mode fiber requires Fiber-Fix FA-06 (white) Epoxy. Combine the resin (white: part A) with the catalyst (amber: part B) using a ratio of 25 to 7 (A to B) by weight in a container and mix thoroughly. Cure time for this epoxy at 85 (±5) degrees Celsius is 15 minutes. Notice: The use of safety glasses for eye protection is recommended.

4.5.1.1 (Continued):

MT Ferrule Termination: Prepare the epoxy according to the fiber type you are working with. Instructions for epoxy preparation are found at the beginning of this section. Turn on the suction pump or prepare suction syringe. Using a toothpick, apply a drop of epoxy through the front edge of the ferrule window and place along the grooves.

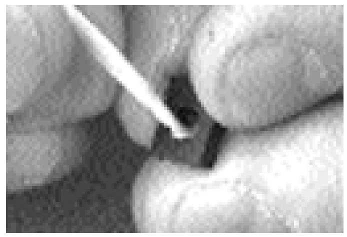


FIGURE 21 - Ferrule Termination Procedure Step 1

Insert the ferrule end face into the suction tube nozzle until the front edge of the ferrule window lines up with the tip of the nozzle. Cover the rear of the ferrule so that the guide pinholes are blocked. Allow the vacuum to draw epoxy through the fiber holes for approximately 5 seconds, or until epoxy has filled all he fiber holes. Note: Failure to follow this step will lead to inconsistent epoxy coverage between the fibers and holes, resulting in poor performance of the connector. After removal from the nozzle, a bead of epoxy covering the fiber holes should remain on the ferrule end face.

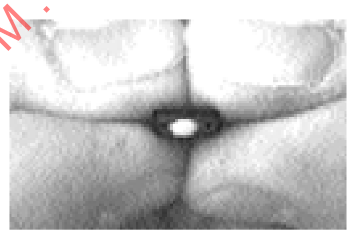


FIGURE 22 - Ferrule Termination Procedure Step 2

With the #1 fiber to the side of the ferrule with the colored dot, insert the fibers into the rear of the ferrule. Tilt the ribbon slightly while looking through the window of the ferrule. Watch the fibers move along the guide grooves and gently insert them into the ferrule. The fibers should slide into the holes smoothly and pass through the ferrule end face; however, if any resistance is felt, back out slightly and try again, watching through the window to ensure that all fibers are in the proper track. Any fiber bending signifies misalignment and will cause fiber breakage.

4.5.1.1 (Continued):

Look into the ferrule window and make sure the edge of the ribbon matrix is located between the back edge of ferrule window and the step marking the end of the grooves. Note: Pushing the edge of the ribbon matrix past the step and onto the grooves may cause the fibers to break. Carefully slide the boot into the back end of the ferrule until it stops. When in proper position the edge of the boot will be visible in the back of the window.

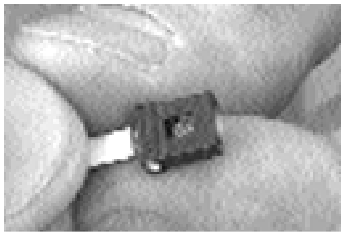


FIGURE 23 - Ferrule Termination Procedure Step 3

Check the end face to ensure there is an epoxy bead around the protruding fibers. If not, carefully apply a drop of epoxy to form the bead, making sure that no epoxy is applied inside the guide pinholes. Apply epoxy into the window until the cavity is full. Take care that no air pockets are formed inside the ferrule cavity.

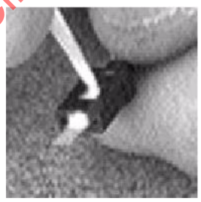


FIGURE 24 - Ferrule Termination Procedure Step 4

Place the ferrule into the ferrule heater. Recheck the epoxy level in the window and add if necessary (some settling may occur due to the epoxy spreading to fill the cavity). Care should be taken not to overfill the cavity, as excess epoxy will have to be removed after curing.

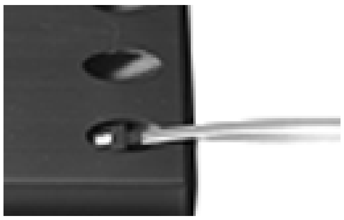


FIGURE 25 - Ferrule Termination Procedure Step 5

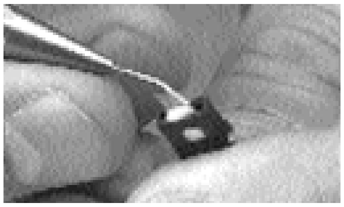


FIGURE 26 - Ferrule Termination Procedure Step 6

4.5.1.1 (Continued):

Follow the cure procedure. This information may be found in the epoxy instructions at the beginning of this section. After curing, remove the ferrule from the oven and allow it to cool. Using a scribing tool, etch the fibers along the epoxy bead on both sides of the ferrule. Grasping the fibers between the thumb and forefinger, gently pull the fibers straight away from the end face.

Route the ferrule to polishing.

Commercial polishing equipment is now available for obtaining the desired end finish of the termini. Figure 27 is a polisher commercially available from USCONEC. Other manufacturers are also offering automated polishing equipment for array ferrules.

FIGURE 27 - Computerized Connector Termini Polishing Equipment
For MT Ferrules Available Through USConec[25]

[25] http://www.usconec.com/Polisher/MTA030.htm

4.5.1.2 Suggested Testing For Array Connectors And Ferrules: A test program should be implemented on all cable plant subassemblies to assure operation over the specified aerospace environment. As a minimum, performance requirements for the connectors and termini will be verified. Testing will be performed to meet the following environmental conditions in accordance with approved MIL or EIA/TIA test methods. Optical Properties will be monitored while the cable assembly is undergoing the following tests in accordance with TIA/EIA-455-XX series of Fiber Optic Test procedures (FOTPs) and Optical Fiber System Test Procedures (OFSTPs). The most common tests include:

Humidity /Temperature Cycling
Salt Spray/Corrosion
Thermal Shock
Thermal Aging
Durability/Maintenance Aging
Mechanical Shock
Vibration
Sand and Dust
EMI/EMP
Power vs. Temperature
Flex Test
Others

4.5.2 High Density Fiber Optic Cable Connectors: First generation fiber optic connectors utilize individual termini for each fiber. With this concept, fibers are individually cleaved, inserted into the termini, and polished to produce a low loss termination. Because of the high fiber count associated with high density fiber optic cables, the alignment and termination hardware generally associated with first generation fiber optic aerospace connectors are not applicable to these cables. The cable-to-cable interface shall be stronger than the cable by itself and the termini block shall be compatible in dimensions with the fiber spacing. To accommodate the utilization of non-eye-safe lasers, a suitable assembly shall be designed to provide eye protection to prevent looking into a fiber end of an unmated connector or power levels shall be restricted to be below the eye-safe threshold during mate/de-mate.

4.5.3 High Density Connector Backshells Properties: The relevant properties of connector backshells, which should be specified, are listed below:

- Backshell Materials
- Plating Materials
- Backshell Dimensions
- Termini Retention Mechanism
- EMI/EMP Shielding Effectiveness
- Cable Strain Relief Mechanism
- Environmental Sealing Methods
- Circular or Rectangular Configuration
- Laser Eye Protection Mechanisms
- Shutters
- Filters

4.5.3.1 High Density Connector Backshells: A suitable connector backshell shall be utilized with high-density fiber optic connectors to permit repeatable alignment of the array termini and shall provide an environmental seal for the enclosed fiber termini. The cables shall be designed to assure that the cable fabric strength members and the connector attachments bear the tension load instead of the optical fibers. High-density connector backshells shall be specifically designed with low mass, and a small footprint and provide for adequate strain relief in cable attachment. An adequate locking mechanism shall be provided to assure reliable operation over the aerospace environment. Array inserts shall provide an adequate alignment mechanism and a means to maintain mating force over the operating environment. The connector mating assembly shall also be stronger than the cables being connected. The connector backshell shall also provide the necessary EMI/EMP protection to prevent unwanted electromagnetic energy from entering the aperture associated with the cable assembly.

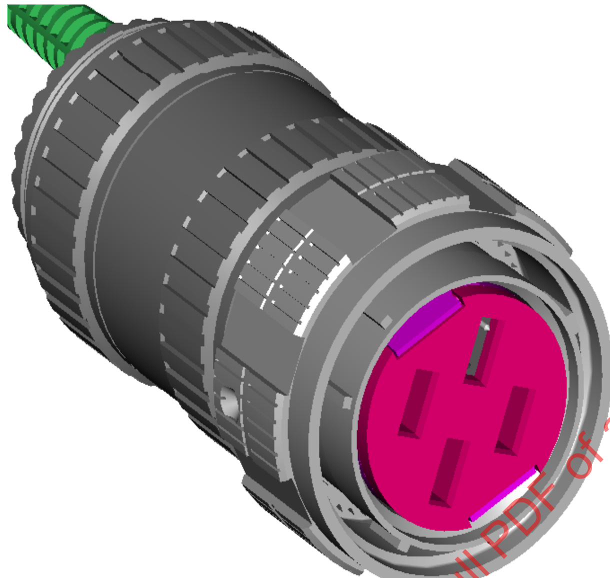


FIGURE 28 - A High Density Connector Backshell With Array Termini (Courtesy Amphenol Corp)

4.6 Silicon Compatible Integrated Optic Devices:

A new family of telecommunications devices is currently being developed utilizing planar waveguide technology, which provides an ideal interface to high-density fiber cables. The most common types of planar waveguide couplers are silica-on-silicon waveguides and ion diffused waveguides. A Sol-gel method of fabrication is also being explored. Couplers are utilized to provide optical power division in an optical system. First generation fiber optic systems have primarily utilized fused biconical couplers wherein a number of fibers are twisted together under applied tension while laser energy is utilized to fuse the fibers together. The fused bi-conical region serves as an optical mixer, which couples the optical energy from any input fiber into all output fibers in a selected power splitting ratio, to produce a star coupler. A tree coupler separates the output from a single fiber into "N" output fibers.

4.6.1 Pyrolytically Deposited Silica Waveguide Couplers: A silica glass planar waveguide coupler is formed by depositing a porous glass on silicon wafers via flame hydrolysis of halide materials such as $SiCl_4$,$TiCl_4$, or $GeCl_4$ (Figure 29). After deposition, the wafers are heated to high temperatures for consolidation to form a vitreous glass. The refractive index is controlled precisely, by changing the flow rate of starting halides. The thickness of the glass is controlled in the range of 10 to 200 µm within 2%. A waveguide is formed by a combination of photolithographic pattern recognition and reactive ion etching. Amorphous silicon is used as a mask material for pattern definition prior to etching of the silica glass. In this photolithographic process, the star and tree waveguide configurations are defined. Ridge waveguides with vertical smooth walls are obtained by selecting suitable etching conditions. A final planar cladding layer is then deposited over the waveguide structure. Both single and multimode versions of these waveguides are commercially available. This materials system is capable of surviving the aerospace environment. Pyrolitically fabricated couplers are available in both multimode and single mode versions.[26]

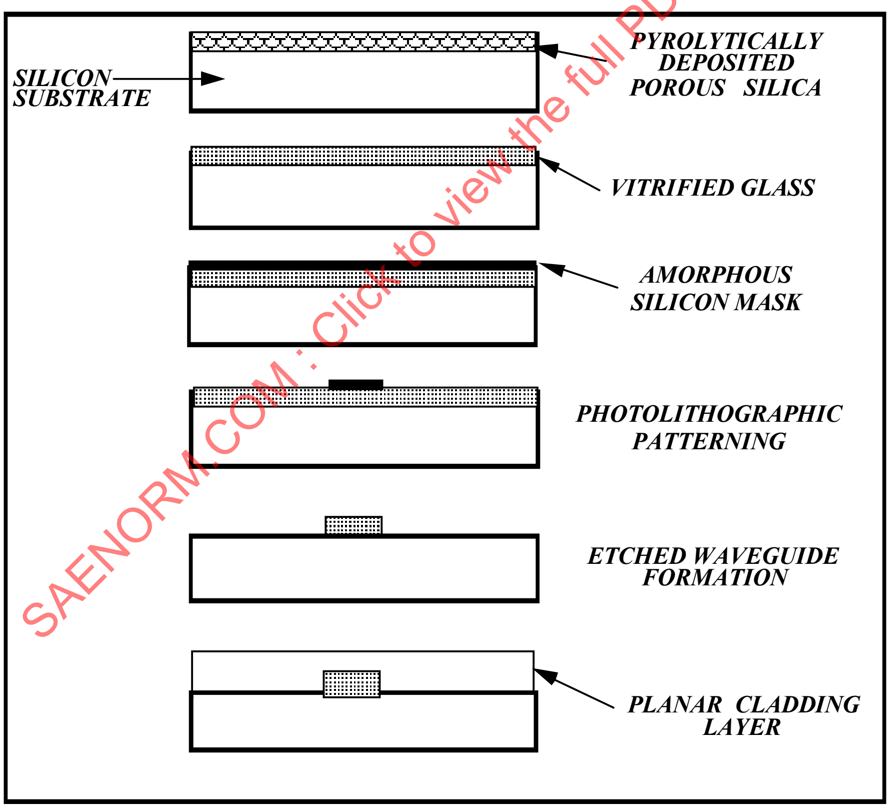


FIGURE 29 - Cross Sectional View of Fabrication Steps for a Planar Silica Waveguide Coupler

26 Miyashita et. al., p. 292

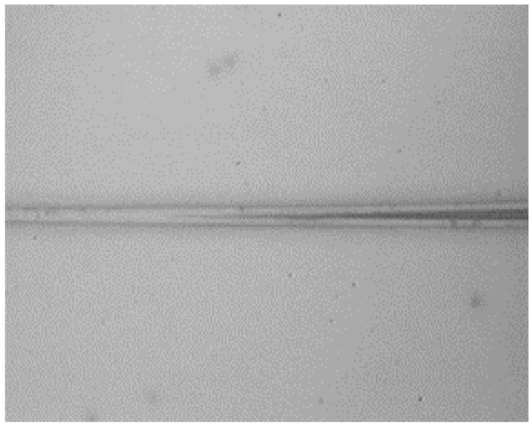


FIGURE 30 - Top View of a Planar Waveguide Coupler

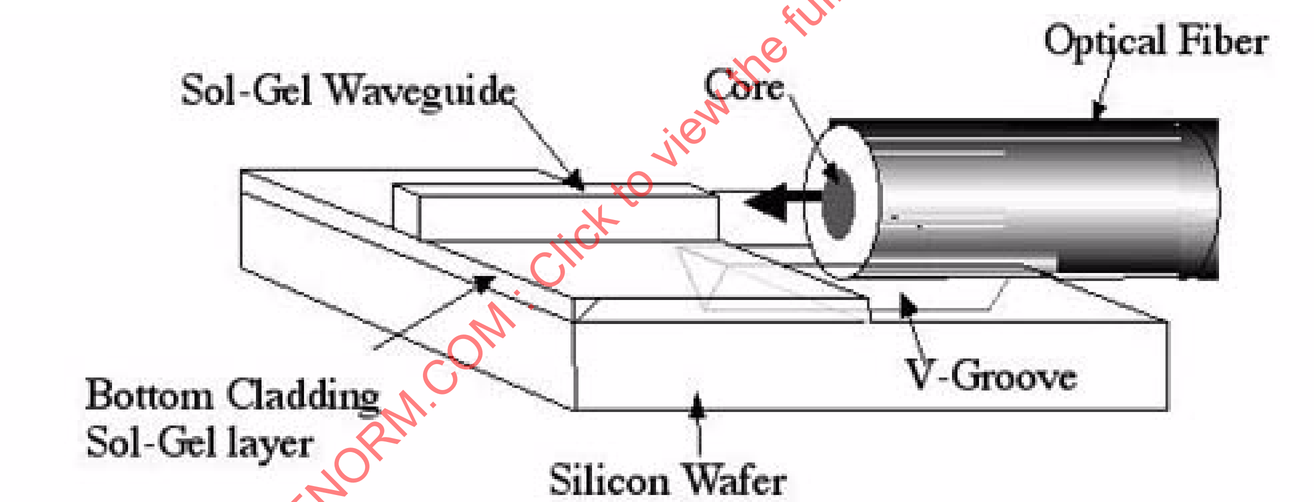


FIGURE 31 - Isometric View of a Fiber to Planar Waveguide V-Groove Alignment

4.6.2 Microchip Couplers Fabricated By The Sol-Gel Method: Microchip couplers and splitters can also be formed by the Sol-Gel method on silicon substrates. The V-groove alignment technique can be utilized to align fibers to these couplers with simplified manufacturing and huge reductions in cost. Figure 30 is an optical photo-micrograph of such a splitter and Figure 31 shows the alignment of a fiber to the waveguide.[27]

27 Li, p.2, p.8

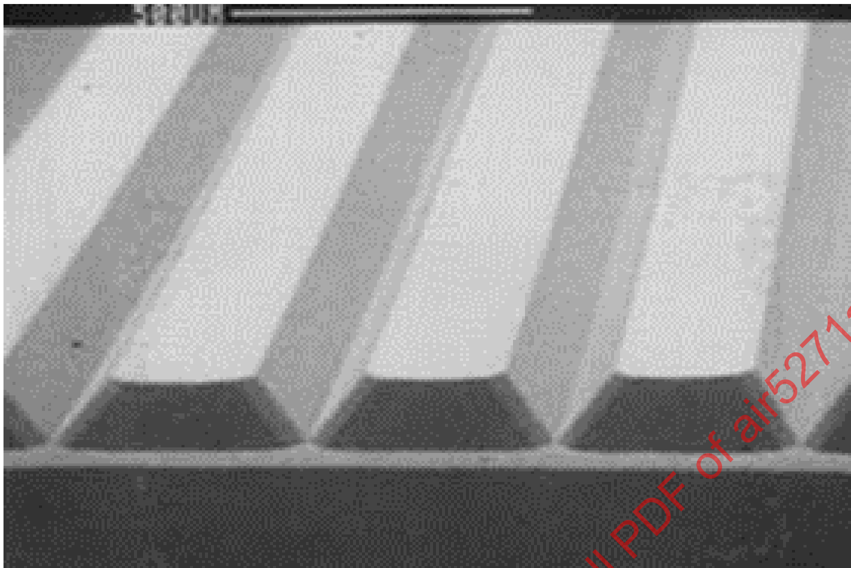


FIGURE 32 - A Photomicrograph of an Etched Silicon Substrate Containing Silicon V-Grooves

4.6.2 (Continued):

To terminate stacked fiber ribbon cables silicon alignment blocks shall be stacked and bonded to provide registration of the fibers in a stacked fiber ribbon cable. Connectors utilizing silicon V-Groove multi-fiber termini are currently manufactured by Berg, AT&T, Fotron Corp. et. al. Figure 32 is a picture of the Mini-Mac commercial connector that utilizes the silicon V-groove termination. The AVMAC connector is an aerospace connector that utilizes the same V-groove termination concept.

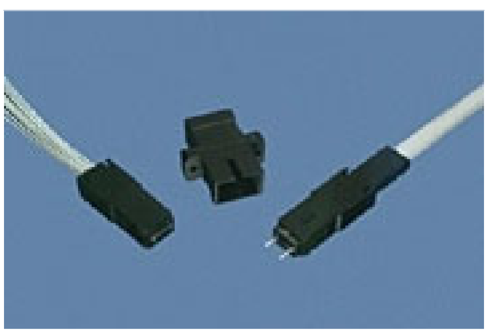


FIGURE 33 - A Molded V-Groove Connector (Courtesy Berg Electronics[28])

[28] http://www.bergelect.com/product/optic/optic_mini.htm

4.6.2 (Continued):

Another solution to the difficulties of fabricating a high-density optical connector is precision molding techniques. One example of such a multiple contact termination connector that is commercially available is the MT connector. The MT ferrule of Figure 33 is a multi-fiber termini that is commercially available in 4, 8, 12, and 16 density for a single connector. Additionally, stacks of five 16-fiber connectors are available creating an 80-fiber connector assembly.[29]

4.6.3 Properties Of Planar Waveguide Couplers: The following properties should be specified:

Waveguide Materials
Waveguide Geometry
Power Splitting Ratio
Excess Loss
Environmental Operating Range
Number of Inputs/Outputs
Input/output uniformity

4.6.4 Active Silicon Optical Circuits: Active Silicon integrated Optical Circuit technology utilizes the processing techniques of the mature silicon micro-fabrication industry to simplify the manufacture of opto-electronic components such as transceivers, switches and sensors. All the advantages of silicon mass-manufacture are therefore immediately inherited by this technology. By using Silicon on Insulator (SOI) wafer processing, monolithic active devices based on low-loss single mode waveguide structures at standard telecom wavelengths can be made (Figure 34). The unusually large cross-section of silicon-on-insulator single-mode waveguides allows excellent mode matching to single-mode telecom fiber. This effect is enhanced by the use of tapered waveguide elements, giving low transmission loss to and from a single-mode optical fiber.

Light in a silicon integrated optical waveguide is well confined because of the large index step from the waveguide to its surrounding material. This allows tighter bends compared to other waveguide technologies, therefore leading to more compact devices. As a result products have smaller footprints, more can be produced per wafer, and reliability is improved as thermal gradient effects are reduced. The stable mechanical properties of silicon significantly ease the task of designing Bookham Corp. products. The transceiver photonic circuitry is written in monolithic silicon-on-insulator chips. Components such as photodiodes, lasers and fibers are attached using rugged hybridization processes.

[29] Satake et al., p.997

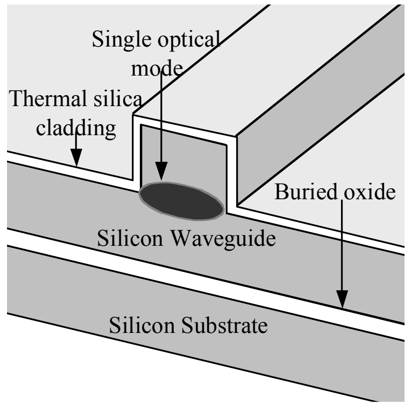


FIGURE 34 - A Silicon Integrated Optical Circuit Structure

FIGURE 35 - A Packaged Transceiver Using Active Silicon Integrated Optical Circuits (Courtesy Bookham Ltd.)

4.6.4 (Continued):

Many application specific devices can be produced using a unique process. The first device to go into full-scale production was a bi-directional 1310/1550 nm transceiver (Figure 35). This transceiver reduces system installation cost through halving the fiber and connector requirements in bi-directional communication applications. Advantages over micro-optic devices include: reduced tracking error, leading to simplification of down stream receiver electronics; improved reliability, due to monolithic design; reduced cost from incorporation of electronic boards, thanks to dual in-line packaging; and considerably reduced production cost.[30]

[30] Knowles et al, pp.1-2

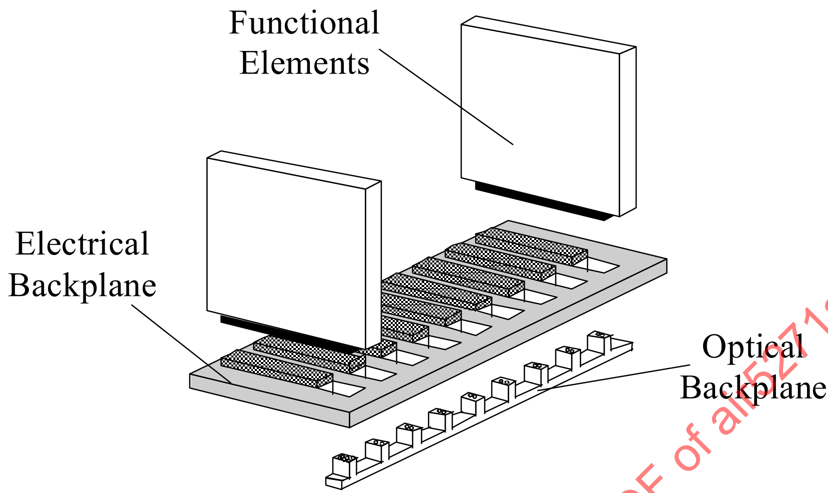


FIGURE 36 - An Optical Backplane as Part of an Avionics Chassis

4.7 Optical Backplane Interconnect:

Currently, multi-layer printed circuit boards (PCBs) are used as backplanes for aerospace computers, and other avionics. An optical equivalent shall accommodate much higher data rates, provide EMI immunity, and permit high fan-out while allowing the physical distribution of modular assets without performance degradation. An optical backplane is a rigid standalone assembly consisting of optical waveguides, optical transmission media connectors and optical couplers which provides structural support for the modules through a suitable connector interface as well as environmental and mechanical protection for the waveguides. Figure 36 depicts an optical backplane integrated into an avionics chassis consisting of modular functional elements interconnected via the optical backplane with power provided using a simple electrical backplane.

The next challenge for implementing optical interfaces is the development of the technology, protocol and physical media standards for optically interconnecting modules within a computer or an electronic rack. Finally, technology and standards for optically interconnecting chips or multi-chip modules (MCMs) on a substrate or electronics card shall be developed as we migrate towards optical computing or more extensive use of optical sensors. Despite the strong advocacy and desirability of such optical interconnect schemes over the years, the solution to these problems have been very elusive. In order for optical interconnect technology to be viable at the module-to-module and chip-to-chip levels, both technological and cost barriers must be overcome. The solution must also be backward and forward fit compatible with accepted electronics packaging concepts and backplane protocols.

4.7 (Continued):

For military systems, an optical interconnect system must be capable of operating over severe environments. This optical interconnect must possess attributes which surpass existing electrical interconnect technology with respect to cost, performance, and physical attributes. The following requirements must be met in order to make optical interconnect technology competitive with electrical interconnects in military systems:

- Operation over shock, vibration and temperature
- Two and three dimensional distribution
- Lightweight, rugged, monolithic structure
- Ease of reconfiguration
- Flexible topologies
- Live insertion and hot swap
- Fault tolerance and redundancy
- High fanout
- Low attenuation and bit error rate
- Extremely high bandwidth
- Low cost, power and latency
- Modular design
- Compatibility with backplane protocols
- Operation in dirty environments

4.7.1 Optical Backplane Construction: The optical backplane assembly consists of three basic components: (1) connectors used to relay the optical signals between the optical backplane media and the functional elements, (2) the optical interconnect media that is use to relay transmissions from one connector to another, and (3) structure used to provide the strength, environmental, and structural support necessary for the entire optical backplane. Figure 37 illustrates these three basic components.

In the following paragraphs, the optional implementation for each of the three basic components will be discussed. There is not one universal "best" selection for each of these implementations. Instead, the selection that is the best will vary between application requirements. The most promising technologies that qualify for use as an optical backplane for interconnecting electronic modules in an aerospace environment include: Embedded Optical Fiber substrates, fiber optic encased ribbons, and polymer waveguides which can be fabricated on appropriate substrates.

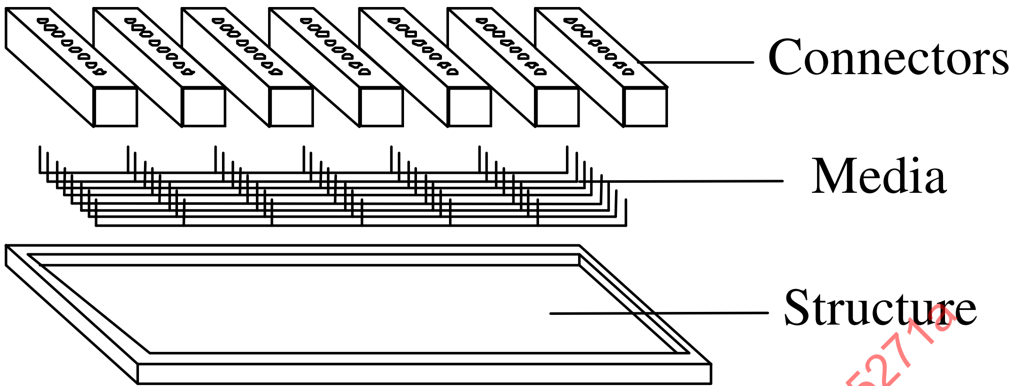


FIGURE 37 - The Optical Backplane Consists of the Connectors, Media, and Structure Components

4.7.1.1 Optical Backplane Connectors: Most optical connectors fall into two classes, those connectors that use a butt coupled approach and those that use an expanded beam technology. Both types have advantages and disadvantages. Butt coupling is the simpler approach. Here the two optical guiding media are brought together in contact and precisely aligned. In expanded beam connectors the optical beam exits the guiding media, is collimated with a lens arrangement and passes through the interface with a greatly expanded beam width. The reverse operation occurs on the other side of the connector. The beam is focused with a similar lens arrangement onto the guiding media. In this section we will explore the connector requirements, different connector technologies and look at various manufacturer designs.

4.7.1.1.1 Backplane Connector Requirements: The module-to-backplane interfaces, provided by the optical backplane connectors, must have characteristics that meet requirements derived from the overall system requirements. The following are some of these characteristics:

Optical Loss: It is anticipated that suitable losses shall be a minimum of 0.5 dB/contact and a maximum of 1.5 dB/contact. Of equal importance with absolute low optical loss, is consistency of optical loss. A connector that has an optical loss of 1.5 dB, no matter how old it is or what environmental conditions it has been used in, will be easier to design into the system than a connector that has a loss of 0.5 dB when new, but which may degrade to 1.25 dB when in use. Absolute consistency of optical loss is not possible; but it is desirable to have all connector optical losses remain within a 1.0 dB range, and to have variation during use of individual connector losses be less than 0.5 dB. Therefore, for the purposes of determining system power budgets, the connectors will be expected to have optical losses ranging from 0.5 to 1.5 dB, with the optical loss of each individual connector staying within a 0.5 dB range in the 0.5 to 1.5 dB total allowed system range.

4.7.1.1.1 (Continued):

Modes Transmitted: Studies of early 21st century aircraft system requirements have indicated that the most severe data networking requirements will occur on tactical aircraft. The data rates anticipated combined with the small physical size of tactical aircraft have indicated that data communications will primarily utilize multi-mode optics. Single mode optics will be necessary for some sensor communication where the signals are transmitted in analog RF form. Therefore, the optical backplane connectors shall support either multi-mode or single mode optical communication.

Fiber Interface: The connectors must be compatible with optical media in which the waveguide characteristic dimension (diameter for round waveguides, width for square waveguides) is typically either 50 µm, 62.5 µm or 100 µm. These dimensions are required for the following reasons:

- Data rates will require laser diode optical sources. Such sources do not require large core diameter waveguides.
- Small core waveguides will be compatible with small area optical detectors in receivers.
- Small area receivers are required for the system to achieve the required data rates.
- 62.5µm graded index waveguides provide the necessary length-bandwidth product to transmit the anticipated data rates over the distances seen within tactical aircraft.
- The thick claddings of 50 µm and 62.5 µm core optical fibers provide low micro-bend losses, making these fiber types desirable for use in aircraft cabling.
- 62.5 µm core optical fibers are common in telecommunication cables, making them easy to obtain from multiple sources at reasonable cost.
- 100 µm core optical fibers are required to be compatible with existing optical interfaces. This is important when considering P^3I insertion of optical backplanes.

Out-of-Plane Bend: Because some potential optical backplane materials are inherently straight and inflexible, the backplane half of each connector mated pair shall be capable of guiding the optical signals to/from the plane of the optical backplane to/from the orthogonal plane of the modules connected to the backplane. In the event that the backplane material is flexible, but requires support in the bend region, the connector shall provide that support unless engineering considerations indicate that forming the bend in the backplane support structure would be a more effective design.

Complexity: Connector complexity shall be minimized, within the constraints of the total body of requirements.

Environment: The connector shall meet the requirements of the environment currently met by tactical aircraft avionics.

4.7.1.1.1 (Continued):

Size: Connector sizes shall be compatible with mounting on the edge(s) of a module and meeting the maximum connectivity requirement. The module size should assure compatibility with commercial and military module standards.

Connectivity: The minimum number of non-redundant optical contacts required for a module is anticipated to be 4 and the maximum number of non-redundant optical contacts is anticipated to be 128 for a module.

Data Rate: The connector shall support digital optical data transmission at signaling rates extending from 0 to 20 GBPS.

4.7.1.1.2 Optical Backplane Connector Technologies: This section describes the various methods for making optical connections between a backplane and modules. The concept of a planar backplane connected to orthogonal modules presupposes the use of connection methods derived from fiber optic technologies. These methods of making the connections fall into two basic optical categories: butt coupled, and expanded beam.

Connector approaches not derived from fiber optic technologies (i.e. free space optics) are possible, but not yet practical for aircraft use, for a number of reasons. Chief among these is that it is not physically practical in an aircraft to arrange processors and memories so that they can directly "see" each other and it is extremely difficult to achieve the necessary stability of the system to maintain alignment of the optical system over environmental extremes when complex optical schemes are employed

4.7.1.1.2.1 Butt Coupled Optical Connector Termini: In these connectors, each fiber in the connector is inserted and bonded into a precisely manufactured ferrule. One ferrule is mounted in the connector on the backplane and the ferrule for the mating fiber is mounted in the connector on the module. When the housings holding the ferrules are mated, the two ferrules touch each other, bringing the fiber end faces to within a few microns of contact or into direct contact, depending upon the exact details of the connector. Figure 38 illustrates the design of a butt coupled optical connector.

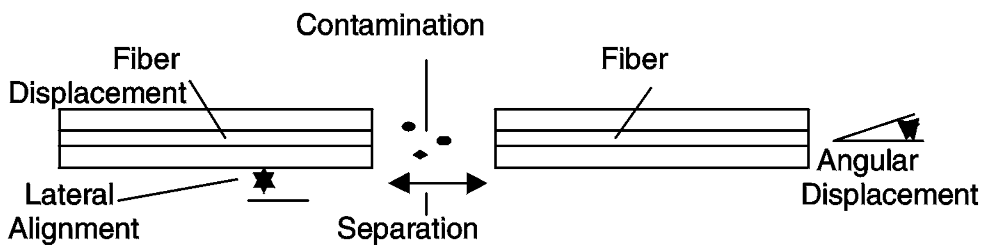


FIGURE 38 - Butt Coupled Optical Connector Design

4.7.1.1.2.1 (Continued):

In these connectors, the optical contacts, usually fiber end faces, must be in very close proximity if the light is to behave as though it is always guided, leading to a low loss connection. If the fiber ends are a greater distance apart than a few wavelengths of the light being transmitted, beam divergence and reflection effects will cause much of the light to be lost at the junction. If the optical end faces actually touch, the losses in these connectors can be very low, because no interface between the optical waveguide and air exists to create reflections.

Butt coupled optical connectors also require good lateral (within a few microns) and angular (within a few degrees) alignment of the optical contacts. To work well, the contacts on opposite sides of a connector must be parallel and aligned along the same axis.

Most optical connectors, particularly the common telecommunications types, such as ST, FC, and SC are single contact connectors of this type. These connectors give good performance in clean, benign environments. In such environments they can provide the good lateral, longitudinal, and angular alignment required for a good butted connection. However, they are not well suited to dirty, harsh environments, nor do single contact telecommunication connectors make sufficiently good use of their internal volumes to be considered for high-density small volume applications. In these connectors, the actual connector volume is much larger than the volume occupied by the optical waveguides themselves. Most of the volume is taken by the support structure for the ferrules. The support structure makes possible the good optical performance of these connectors, but with the drawbacks of size, complexity, and expense. Size is the greatest problem with these single contact connectors. They are sufficiently large that, were they to be installed on the edge of a module, only a single row of perhaps ten connectors would fit, falling far short of the maximum connectivity required. For this reason, it is likely that some form of multiple contact termination (sometimes called a "Mass Termination") will be required. An additional difficulty with single contact telecommunication connector designs is that, except for the SC, all these connectors require some form of twisting motion during the mate/de-mate process. That is not a problem for single contact connectors, but it is difficult to extend to multiple contact systems.

A potential solution to the difficulties of fabricating a high-density optical connector lies in increasing the number of contacts per connector, or even per ferrule. This approach has been taken in the development of multiple contact connectors in which the "ferrule" is a small block in which grooves have been etched. Optical contacts in this type of connector are the fibers themselves, and they are glued into the grooves.

One example of a multiple contact termination connector that is commercially available is the MT connector. The MT is a multi-fiber connector that is currently available in 4, 8, 12, and 16 density for a single connector. Additionally, stacks of five 16-fiber connectors are available creating an 80-fiber connector assembly.

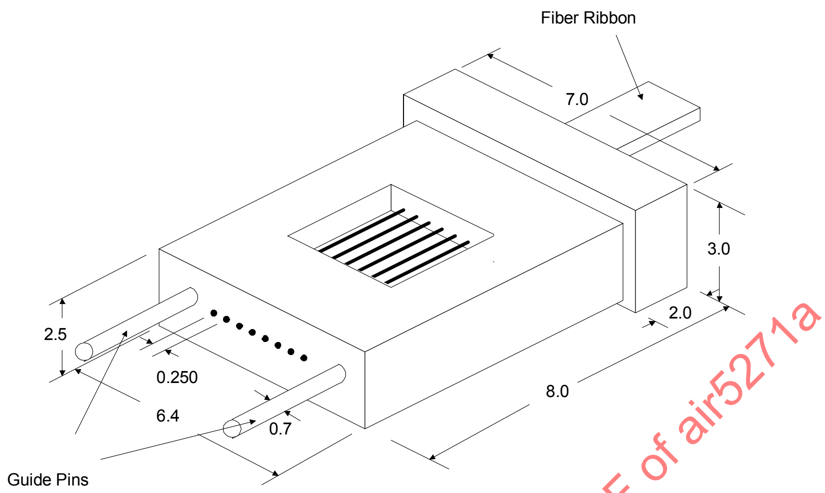


FIGURE 39 - MT Optical Connector (Dimensions in mm)

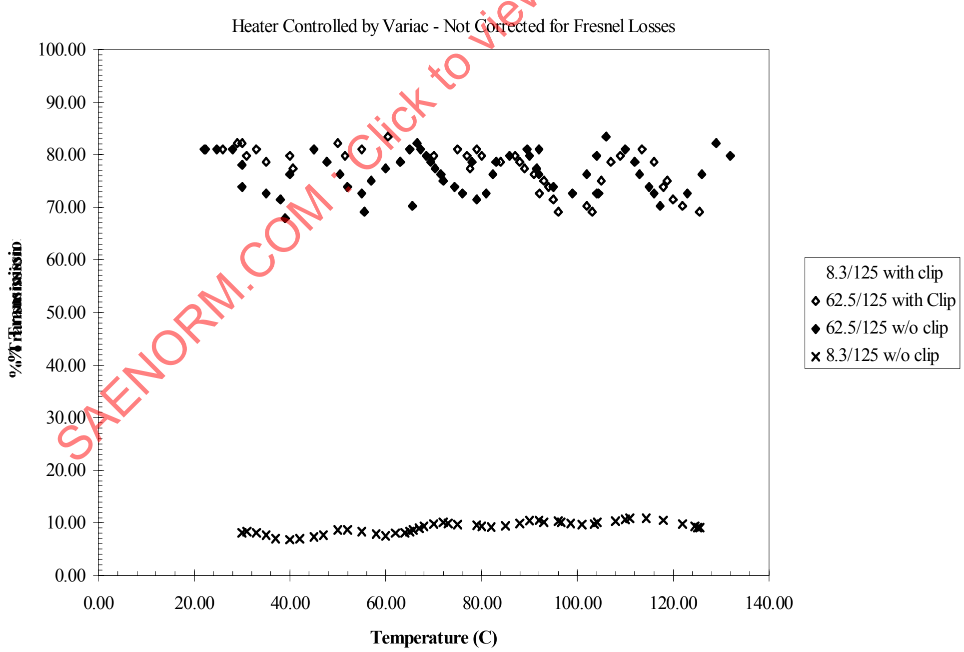


FIGURE 40 - MT Connector Transmission Vs. Temperature

4.7.1.1.2.2 MT Array Connector Termini: The MT connector is a multi-fiber, commercial, optical connector that is available in up to a 16 fiber configuration. Figure 39 shows the MT termini size and shape. The body is molded from low expansion plastic or ceramic with two steel pins providing the precise fiber alignment. The body of the connector has a molded set of V-grooves ending in an array of holes. Fibers are bonded to the V-grooves and extend through the holes. After bonding, the fibers are cleaved and the array is polished. This connector is available from a variety of vendors, such as USCONEC, Alcoa Fujikura, NGK-LOCKE, LTD. and their distributors. Some form of spring is used to keep a positive force on the connector halves. The average insertion loss for all fibers is 0.5 dB with maximum loss for the fibers <1.0 dB. After 1000 mate/de-mate cycles, the change in connector loss is less than 0.2 dB. Its temperature range is given as -30 to +70 °C. The connector has been tested up to +125 °C with <15% periodic fluctuation due to an interference effect caused by the thermal mismatch between the glass fiber and the plastic housing (Figure 40). If this signal variation poses a problem, the problem can be minimized by applying anti-reflection coatings to the fiber ends.

The MT connector is attractive because of its simplicity, low cost and potential for militarization. In the OBIS program we will incorporate the MT connector into one of the backplane designs and test its performance against required military environments. Here the connector holders have been modified to accommodate the MT connectors. Figure 41 shows the optical backplane with MT connectors on the backplane assembly and MT connectors and holders on the module of the fabric card.

The MT connector is attractive because of its simplicity, low cost and potential for militarization. In the Optical Backplane Interconnect System (OBIS) program Lockheed Martin and Amphenol Aerospace have developed a removable/replaceable optical/electrical backplane featuring MT connectors (Figure 42). The MT connectors are being incorporated into one of the backplane designs and the performance tested against required military environments. Here the connector holders have been modified to accommodate the MT connectors. Figure 40 shows the evolved optical backplane with MT connectors on the backplane assembly and MT connectors and holders on the module of the fabric card (Figure 43).

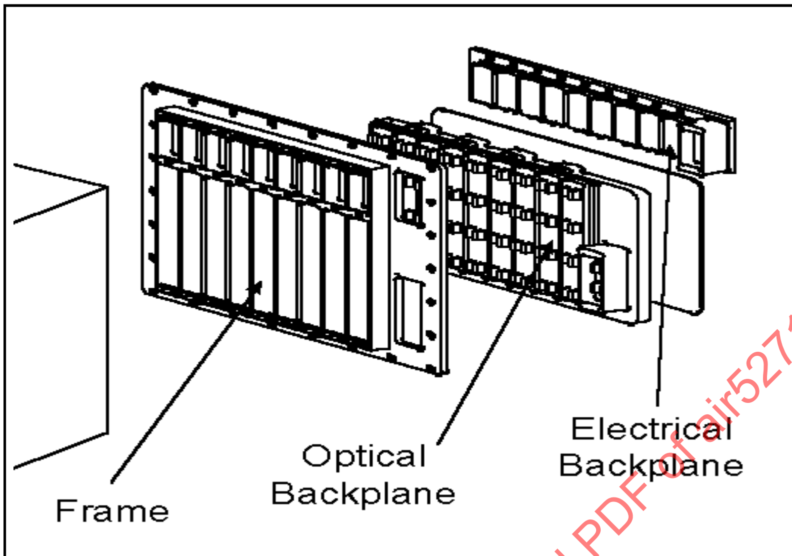


FIGURE 41 - An Optical/Electrical Backplane

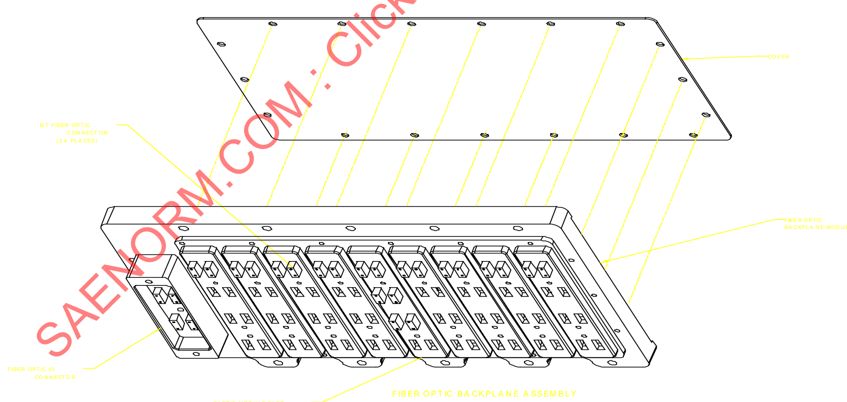


FIGURE 42 - An Optical Backplane

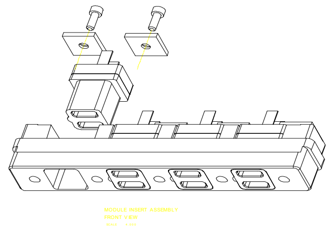


FIGURE 43 - Housing for the MT Connectors

4.7.1.1.2.3 Ceramic Array Connector Termini: Page Automated Telecommunication Systems, Inc. (PATSI) has developed a ribbon fiber cable that is strengthened and encased within a weave of material. This fiber encased weave ribbon configuration provides a multi-channel optical path between boxes and between modules within the box. A multi-fiber MT connector could be attached to the ribbon ends. In addition, PATSI has developed the designs for a connector that can be militarized and is now in the process of fabricating prototype units under the OBIS program. The PATSI connector uses a multi-channel ceramic plate with precision drilled alignment holes to provide fiber alignment and a housing that is approximately the same size as the AT&T ROC connector. In its present form this connector provides butt coupling, however, PATSI claims the design could be lensed to provide multi-channel, expanded beam, optical interconnections.

4.7.1.1.2.4 Silicon V-Groove Connector Termini: Under the DARPA sponsored FLASH program, FOTRON Inc. has developed a multi-fiber connector that is adapted to either a bulkhead connector or to a backplane connector. This connector uses a V-groove approach combined with a glass cover plate to align the fibers within the multi-fiber positioner (MFP). The MFP can accommodate either fibers or an array of polymer waveguides. The MFP is mounted within the connector shell using a floating-contact concept to provide vibration isolation and physical contact of fiber end surfaces. One version of this connector provides four inserts, each with four fibers, in a MIL-C-38999 receptacle (shell size #19). Another version provides a single insert with four fibers in a shell size #11 MIL-C-38999 receptacle. The MFP concept has been extended to provide a multi-fiber, ribbon cable splice that is completely environmentally protected and allows practical field use in adverse conditions. These connectors and splices are designed for -55 to +200 °C operation and to survive 45 gs random vibration on each of its three axis. Additional improvements on this connector design have been made under the X-33 Re-useable Launch Vehicle (RLV) Program (Figure 6). The backplane version uses the same MFP concept but now uses alignment rails to provide a blind mate capability for fiber ribbon positioning. This design also provides for a multi-channel polymer waveguide array to be used on one or both connectors.

4.7.1.1.2.5 Expanded Beam Optical Connector Termini: Connectors of this type differ from butt coupled connectors in that the beam is allowed to exit the optical waveguide and some form of refractive or diffractive optics is used to expand and collimate the unguided beam. The expanded beam then crosses the interface between the two halves of a mated connector where more optics focuses the beam into the receiving waveguide. Figure 44 illustrates the design of an expanded beam optical connector. This provides advantages in that the expanded beam is more resistant to variations in the separation between the two halves of the connector, is more resistant to lateral misalignment, and is more resistant to contamination than a butt coupled connector. However, expanded beam connectors are more sensitive to angular misalignments than a butt coupled connector. Furthermore, the presence of all the optical devices and the interfaces between the waveguide material, the optical devices, and the surrounding medium (usually air) causes these connectors to exhibit optical losses greater than butt coupled connectors. For these reasons, expanded beam connectors have rarely been applied in the telecommunications industry. Telephone systems require the absolute lowest optical loss possible. The higher optical loss of expanded beam connectors made them unattractive to the telecommunication industry; also, considerable attention would have to be given to controlling angular alignment. For better optical performance, telephone companies were willing to expend the space and money to build around butt coupled connectors whatever structure was necessary to keep them clean and achieve the low losses that are possible with those connectors in a ground-based environment.

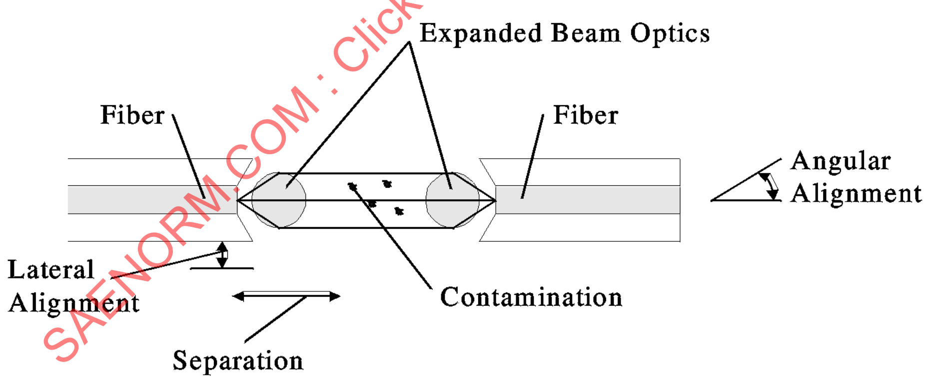


FIGURE 44 - Expanded Beam Optical Connector Design

The situation in the aerospace industry is different from that for telecommunications. Though achieving low optical loss is important, consistency of optical loss in a light weight, low volume connector in the face of harsh and dirty environmental conditions is more important. Consequently, expanded beam connectors are a viable possibility for aerospace applications. Figure 45 shows a Generation I lensed fiber optic connector utilized on the Boeing 777 Aircraft manufactured by ITT Cannon.

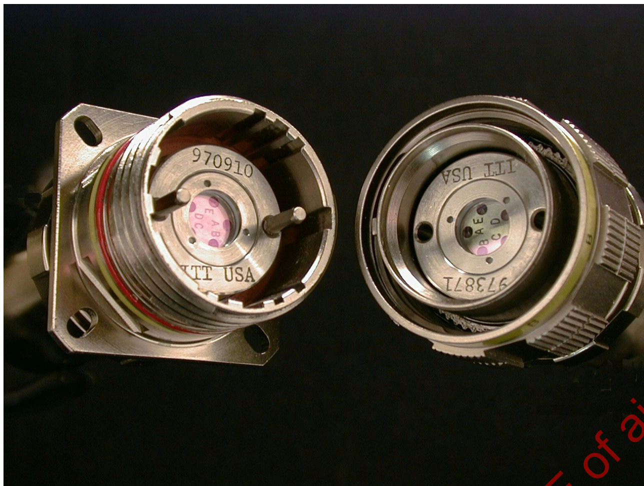


FIGURE 45 - A Generation I Lens Fiber OpticConnector used on The Boeing 777 Aircraft (Courtesy ITT Cannon and Boeing Corp.)

4.7.1.2 Optical Backplane Media: The optical backplane media is the optical material used to interconnect the module cards to each other. The optics portion consists of optical fibers or polymer waveguides (we are not considering free space at this time). Information in the form of light pulses flow through the backplane media. The packaging of the optical media takes different forms. This section will describe the various backplane media and the different methods used to package them.

4.7.1.2.1 Embedded Fiber Backplanes: Standard communication optical fiber can be used in a backplane configuration. Fibers such as 50/125 µm or 62.5/125 µm step index or graded index have been used. The short distances involved in a backplane structure eliminate the problems of modal or chromic dispersion. For avionics application a graded index, radiation hardened 100/140/172 µm fiber is normally used. This fiber has a special hermetic polyimide coating for added environmental protection. Further protection is provided by the jacket of these fibers. For F-22 applications, the individual fibers are surrounded by a Tefzel jacket 900 µm in diameter.

Fiber optics techniques utilizing single mode fibers have also been combined with multi-layer printed circuit fabrication to develop a fiber-in-board technology for optical fiber backplanes, fiber management etc. The technology has already been used to produce a 64 way single mode optical fiber backplane (~25 x 12 x 0.5 cm) incorporating a 16 x 16 star coupler (Figure 46).[31]

[31] Small ,1995, Section 10.3, 1996, Section 8.2

4.7.1.2.1 (Continued):

The backplane was developed as part of a study into the implementation of single mode fibre data networks for Integrated Modular Avionics systems. The backplane has already demonstrated excellent optical characteristics under demanding environmental tests including -53 to +90 °C temperature cycling and gunfire vibration (~4 minutes at 28 g RMS) which is particularly severe.

The fiber-in-board technology is quite versatile and not just limited to optical backplanes. It can, for example, be used for fibre delay lines and fibre gyro loops and can be further developed to allow the incorporation of active opto-electronic components in the same board.

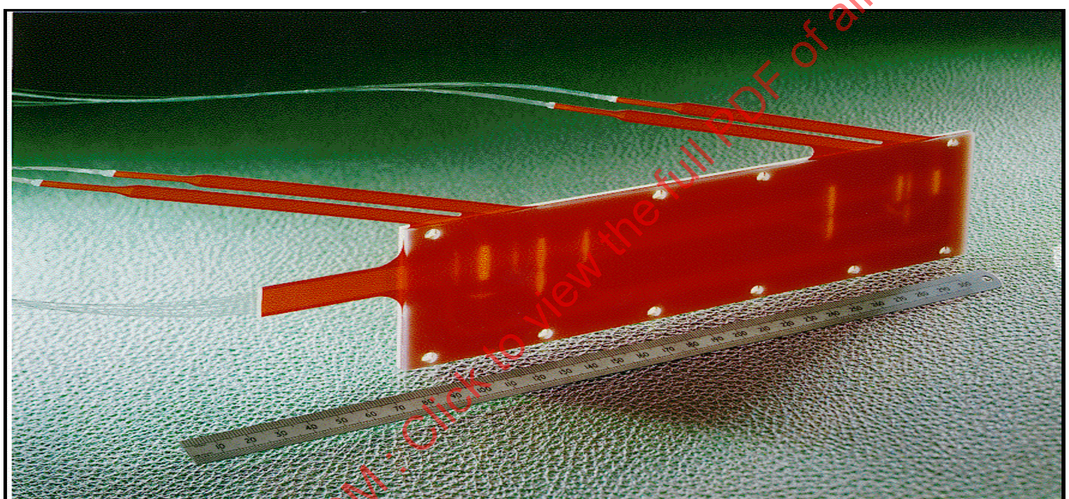


FIGURE 46 - An Embedded Optical Fiber Backplane (Courtesy GEC Marconi)

4.7.1.2.2 Polymer Waveguide Backplanes: In addition to optical fibers, waveguide structures are a promising candidate for optical backplane applications. These waveguides are made from several layers of polymer material. The substrate, cladding and waveguide are polymer sheets with different index of refraction. They are laminated together and the waveguide pattern is photo-lithographically produced. The advantage is the potential for low cost batch fabrication of complex waveguide patterns. This material has more loss (0.1 to 0.2 dB/cm) than optical fibers but on a backplane the lengths of the channels are short so the total optical loss is tolerable. The lowest loss region is in the short wavelength region, however, development is underway to make low loss guides in the 1300 nm range so advantage can be taken of all the component development efforts in that region of the spectrum[32].

[32] Bogenberger, D., Chap. 23

4.7.1.3 Optical Backplane Structure: The interconnecting backplane optical fibers or polymer waveguides can be encased in various media. Some protection surrounding the fibers or the waveguides is required and can be as simple as the outer jacket of the fiber. A foam structure holding the polymer waveguides in place, fully embedding the fiber bundle in a urethane foam, a solid epoxy, or perhaps a semi-rigid gel like structure provides additional protection. Surrounding the fibers with a structural weave of protective material before encasing the entire bundle results in a more solid structure.

4.7.1.3.1 Rigid Backplane Structure: Embedded fiber backplanes shall utilize glass or plastic fibers or fiber ribbons that are encased in a structurally reinforced epoxy resin to form a monolithic substrate. Connectors utilizing ribbon termini concepts shall be applied to the fibers prior to embedment and shall also be embedded in the composite backplane material. Figure 44 depicts an embedded fiber composite backplane. These structures are designed as low cost assemblies and are non-repairable. They must be replaced in their entirety if a malfunction occurs.

4.7.1.3.2 Removable/Replaceable Semi-Rigid Assembly: A second approach for an optical backplane assembly is to design repairability into the structure. In this approach parts of the backplane are designed to be removed and either repaired or replaced. For example, the OBIS program provides a backplane assembly in which the optical strip between any module card and the interconnect fabric module can be removed. Figure 47 shows the four interconnecting strips and the media assembly of the OBIS concept demonstration model. Each strip consists of four channels with expensive connector termini attached at each end. The four strips are then stacked together and surrounded by a metal holder. All termini would be lost if there was a damaged part and the entire backplane was a rigid assembly. With each strip removable, only those termini on the damaged strip would be lost.[33]

4.7.2 Optical Backplane Parameters: Connectors for the module-to-module interface must have characteristics meeting requirements derived from overall system requirements. Parameters specified for backplane connectors shall be identical to those of optical cable connectors and shall be specified to meet an overall system power budget. Backplane media losses shall likewise be specified to meet the power budget of the system.

[33] Stevens et. al., OBIS Phase I Trade Study

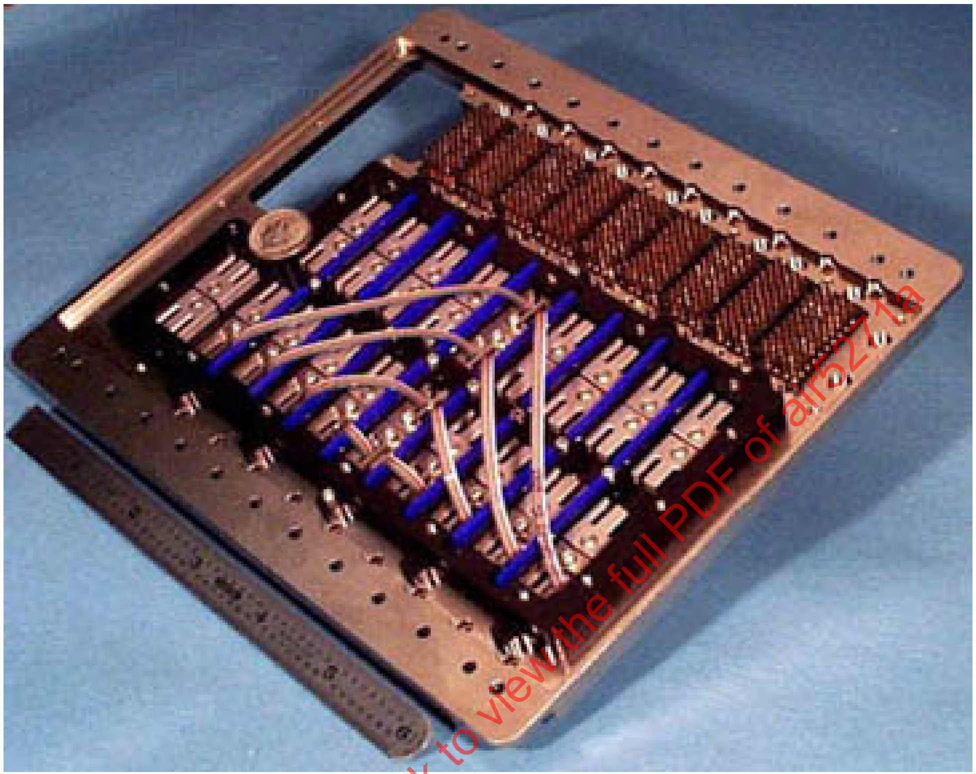


FIGURE 47 - Optical Backplane Media Strips and Assembly (Courtesy Amphenol Corp.)

4.8 Opto-Electronic Source/Detector Devices and Packaging:

The needs of high performance and the capabilities of optical communications have continuously evolved and converged in the last two decades. Microchip electronics technology has outpaced the ability to improve electrical wire interconnections between remotely located components such as sensor subsystem modules. As the bandwidth increases, the critical length decreases at which electrical loading and signal skew becomes a limitation. These interconnections are now a major limitation in the overall system speed of fast computers.

Optical transmitters, receivers and fiber connectors are prevalent for discrete transmitters, discrete receivers and single fibers. However, the short link parallel interconnections for computer backplanes demand integrated transmitter array modules, integrated receiver array modules, coherently bundled fiber arrays, e.g. fiber optic ribbon cables, and standardized compatible connections for connecting the transmitter/receiver array modules to the fiber stacked ribbon cables. These opto-electronic array components will require low-profile hermetic packages, which can survive the severe aerospace environment.

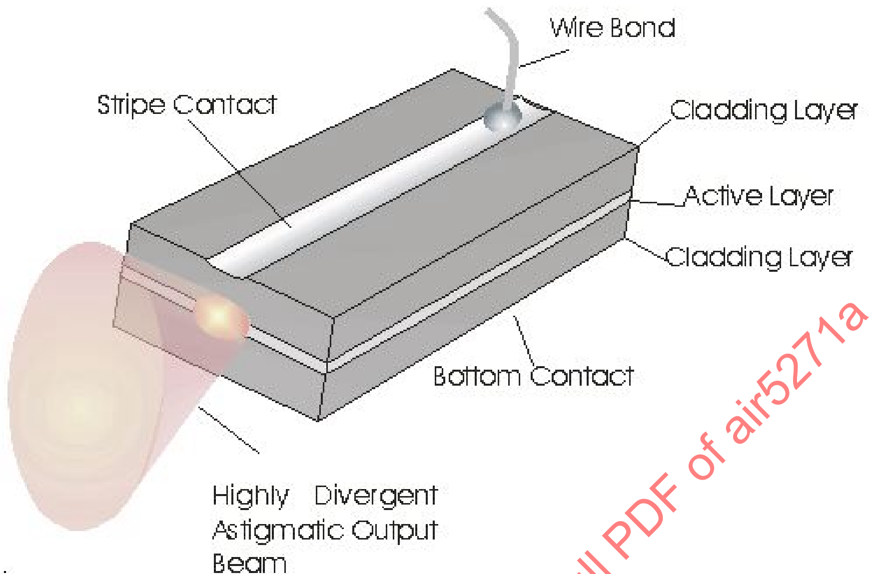


FIGURE 48 - Edge Emitting Laser[34]

4.8.1 Edge Emitting Heterojunction Lasers: Hetero-junction edge emitting lasers (Figure 48) have broad utilization in the commercial telecommunications industry. The devices are optimized for use in the 1.3 or 1.5 µm low attenuation window of optical fibers. These devices typically exhibit threshold currents of around 20 mA with greater than 20% quantum efficiency. Most commercial devices will not operate over the full aerospace temperature range and are not hermetically packaged. A pigtail is used to couple the optical energy to a fiber. The linear nature of the emitting junction produces an elliptical emission pattern which makes coupling to a circular fiber inefficient. Recently, strained quantum layer hetero-junctions have been developed which have operated reliably over the complete aerospace temperature environment and a low profile hermetic package has been developed.

Linear arrays of edge emitting hetero-junction lasers have been demonstrated at several major research laboratories for use in parallel computer interconnects. These arrays with spacing of approximately 250 µm are coupled to ribbon fibers to send sixteen or thirty-two bit words between processing elements in a computer at gigabit/sec data rates. Efficient packaging presents a challenge because of thermal and optical constraints that may impede reliable operation over aerospace environments.

34 http://britneyspears.ac/fplasers.htm

4.8.2 Vertical-Cavity Surface-Emitting Lasers (VCSELS): Vertical-cavity lasers are a new family of semiconductor laser devices that have existed in concept and in prototype demonstrations since the late 1970s.[35] But it was not until the late 1980s, when continuous-wave low-threshold-current VCSELs were demonstrated at room temperature, that practical viability for numerous applications began to be envisioned.[36,37] Equally important is the capability to produce VCSELs and VCSEL arrays in a manner consistent with low-cost manufacturing approaches. Early attempts to fabricate full VCSEL wafers using standard batch fabrication techniques yielding devices with adequate performance was made possible with the demonstration of a planar, implanted top-emitting structure operating nominally at 850 nm (Figure 49).[38,39]

By avoiding the need for through-substrate transmission, this structure allowed more flexibility in emission wavelength, including wavelengths compatible with both low-cost GaAs and Si-based detectors.[40,41]

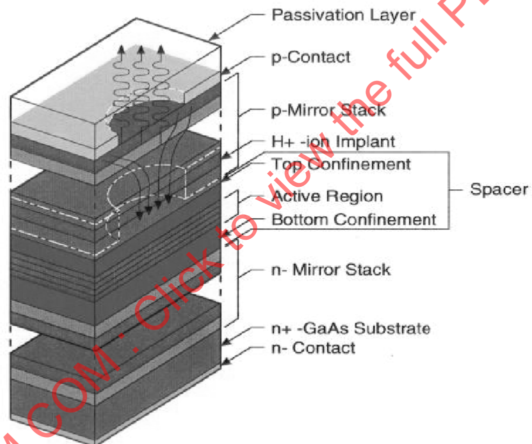


FIGURE 49 - Cross Section of Implanted VCSEL Structure

35 Koyama et al, .pp. 1845-1855
36 Ibaraki et al. pp. 667-668
37 Jewell et al., pp. 210-214
38 Lee et al., pp.710-711
39 Morgan et al, pp. 149-159
40 Morgan, SPIE pp.64-89
41 Fiedler et al., pp. 1664-1665

4.8.2 (Continued):

There is currently a strong catalyst for VCSEL-based technology in the area of high-speed (within an order of magnitude of 1 Gbit/s), medium-distance (1 m to 1 km) commercial data links.[37,38,33,40,41,42,43] These applications would include but are not limited to:

- LAN backbones,
- links to remote peripherals,
- interconnections for workstation clusters,
- cabinet-to-cabinet links within supercomputers,
- backplanes for massively parallel processors,
- telecommunications switching,
- and links from storage systems to computer hosts[37-39,43].

These links must be manufactured with adequate performance, reliability and packaging. Additionally, initial commercial insertion is most likely to come about by upgrading existing electrical (e.g., copper-wire based) and optical data links with VCSEL-based solutions, exhibiting an increase in performance with no sacrifice in cost[37].

Exploiting VCSEL performance advantages, combined with producibility competitive with existing high-performance edge-emitting laser and LEDs, is resulting in single-channel, high-speed VCSEL-based transceiver products from several vendors. The realization is that the entire module cost can be reduced, not necessarily because of the low-cost VCSEL but due to simplification of the transceiver module [37-39]. For example, easier thermal management and simplification of the driver chip are possible due to the low (<10 mA) operating currents and voltages (<2 V), and a threshold current that can be made insensitive to temperature as is shown in Figure 50. Stability over time would again eliminate the need for complex monitoring and feedback circuitry. This last requirement implies good reliability. Indeed, these VCSELs have now demonstrated reliability $>5\times10^7$ hours mean time to failure (MTTF) (at room temperature and operating current)[44], comparable to if not better than existing optical sources (LEDs, CD, and telecommunication lasers). Moreover, due to the lower divergence (and inherently circularly symmetric) beam characteristics, coupling to fiber is clearly simplified (looser alignment tolerances, cheaper or complete elimination of a coupling lens, etc.). Coupled with the demonstrated multi-gigahertz speed of VCSELs [38-43], this should give performance superior to LED-based links and even CD-laser-based links while still being cost-competitive, and ultimately should give performance comparable to but less costly than telecommunication-grade laser-based local area networks.

42 Lehman et al, pp. 1251-1252
43 Wong et al., pp. 995-1016
44 Guenter et al, (in this volume)

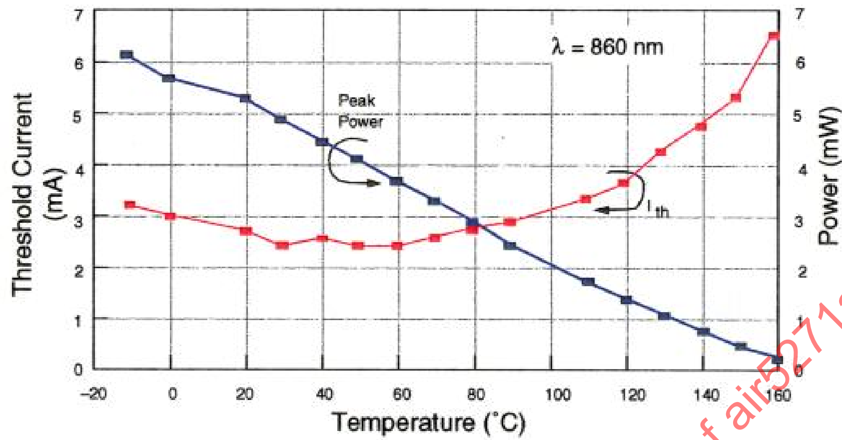


FIGURE 50 - Temperature Dependence of Threshold Current and Output Power

4.8.2 (Continued):

Intermediate-term applications could come from parallel (1-D or 2-D) fiber links such as those initially demonstrated within the Opto-electronics Technology Consortium (OETC)[38-43]. This allows a natural extension to higher aggregate bit rates while amortizing packaging costs over multiple lines for a single transmitter or transceiver. There may also be advantages in the simplification of multiplexing and de-multiplexing electronic circuitry using parallelism at these data rates. It is important to note that the demonstrated uniformity and yield of VCSEL arrays may be exploited to simplify parallel modules and lower costs.

Finally, VCSELs have the unique geometric advantage of being amenable to two-dimensional arrays, which will make them tractable for increasing interconnect parallelism, squaring the potential data throughput yet maintaining element bit rate. Additionally, 2-D arrays of lasers could very well serve as the ultimate source for future applications, such as within smart pixels or multi-chip modules, confocal imaging, displays and spatial-light modulators, or even simply as a source of high optical (potentially coherent) power. The unique ability and flexibility to control the emission characteristics may open up a number of potential applications in the next century.

4.8.2.1 Long Wavelength VCSELS: Recently, investigators from Gore Associates have described a new structure that has demonstrated CW operation to 80 °C, 1.3 mW power at 25 °C, and virtually all the power in a single longitudinal and transverse mode with emission at 1300 nm. Figure 51 shows a schematic of the device structure. The structure makes use of two wafer-fused GaAs/AlGaAs mirrors. The mirrors and active region are undoped, and the structure includes an 850 nm VCSEL vertically adjacent to the 1300 nm VCSEL. The electrically pumped 850 nm VCSEL optically pumps the 1300 nm VCSEL, which then emits out the top through the 850 nm VCSEL. The 1300 nm mirrors only produce 1 to 2% reflection at 850 nm and vice versa, so the two laser cavities can be designed independently of each other. By controlling 1300 nm VCSEL reflectivity, the structure has the flexibility to be either a top-emitter or bottom emitter. The undesired 850 nm emission is suppressed through substrate absorption (bottom-emitter) or high 850 nm top-mirror reflectivity (top-emitter).

"This structure has several fundamental advantages over direct electrical pumping. First, the undoped 1300 nm optical cavity has greatly reduced free-carrier losses. Second, the wafer fusion now provides only an optical interface, so it does not introduce additional device voltage. This allows the device voltage to be the typically low voltage of an 850 nm VCSEL. Thirdly, resistive heating is primarily confined to the 850 nm pump. Spectral measurements show that the 1300 nm VCSEL temperature rise is less than half that of the 850 nm VCSEL. Lastly, the absence of current crowding and reduced thermal lensing allows higher single-mode powers".[45]

4.8.2.2 Tunable VCSELS: VCSELs and LEDs are promising devices for free-space and fiber communication systems. Their advantages include low threshold, single mode operation, a circularly symmetric beam profile and efficient coupling into fibers. Commercially they are attractive because they can be processed readily and tested on wafer. As opposed to conventional edge-emitting laser diodes, VCSELs can be formed into two dimensional laser diode arrays, thus enabling many new applications for semiconductor lasers.

[45] Jayaraman et al. ,W.L. Gore website

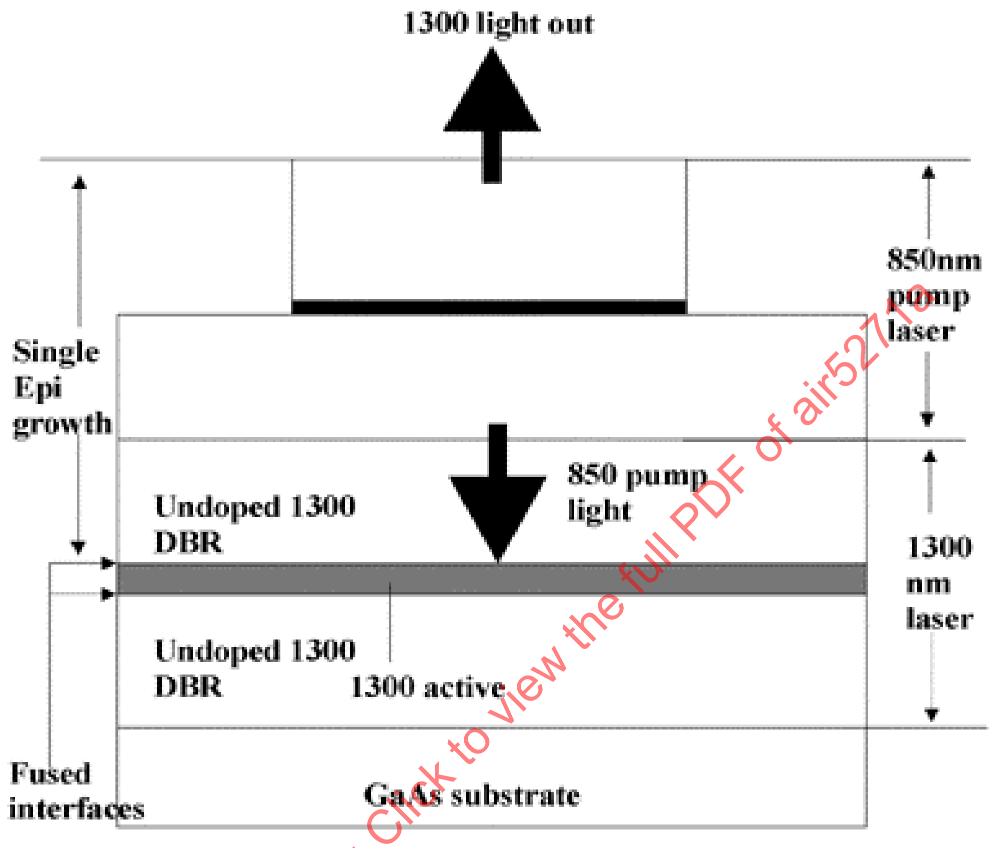


FIGURE 51 - Schematic Of Double-Fused 1300nm VCSEL Device Structure[46]

4.8.2.2 (Continued):

It is said that the "vertical-cavity laser is to photonics as CMOS is to electronics" and several VCSEL-based transceiver modules are now being offered commercially. Hewlett-Packard has a 1.062-Gbit/second transceiver, packaged in a 1x9 configuration, as well as Gigabit Ethernet Transceiver. Vixel Corporation and Honeywell Corporation are bringing out a 1-Gbit/sec VCSEL-based component for fiber-optic applications; and Sun Microsystems, using VCSEL technology, has put together what it calls the fastest ATM networking board available today.

Fueling the excitement surrounding VCSELs are the recent achievements of striking performance gains and size reductions. Early lateral-emitting diodes had an awkward 5 micrometer x 1000 micrometer geometry; the latest VCSELs have a round aperture. In addition, the diodes radiate light vertically, making them convenient for packaging in array configurations.

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[46] Jayaraman et al. ,W.L. Gore website

4.8.2.2 (Continued):

New devices are being manufactured with greater than 99 percent yield, and the newer oxide-contained diodes have pushed the threshold current from around 1000 mA to below 10 mA; these VCSEL breakthroughs will be a key enabler for VLSI photonics. The current research goal is to push to 4 square microns and develop packaging and mounting techniques to integrate them with CMOS VLSI chips.

4.8.2.2.1 Micro-Machined Wavelength-Tunable VCSELS: Implementation of Wavelength Division Multiplexing (WDM) using fixed wavelength laser arrays have temperature-control, system reliability, component aging and manufacturability problems. Because of these shortcomings, wavelength tunable lasers are indispensable elements of such an array since the lasing wavelength can be set, maintained or changed to any wavelength within their tuning range. Due to their long cavities, edge-emitting lasers have small mode spacing, which limits the continuous tuning range. Tuning beyond this causes the laser to mode hop. On the other hand, vertical cavity lasers have short cavities (wide mode spacing) which enable one to achieve continuous wavelength tuning without mode hopping. The wavelength tuning range can be made as wide as the gain spectrum of the laser. Therefore, the challenge is to develop wavelength tunable vertical cavity devices to satisfy the unique requirements of WDM architectures.

Some of the necessary components exist today, some are in development and some are just concepts. Research Teams at Stanford University, CA and the University of Sheffield, England, have employed approaches based on micro-machining to make variable wavelength VCSELs. The device is a conventional VCSEL structure with bottom mirror and cavity. The top mirror is part of a deformable membrane that is suspended above the semiconductor cavity by an air gap. The air gap thickness can be modulated electro-statically by applying a bias between the membrane and the cavity. The "new" laser cavity is then made up of the semiconductor cavity plus the air gap. Using this approach the research teams have been able to fabricate tunable filters with 30 nm tuning range, LEDs with 39 nm range and VCSELs with a record 19.1 nm continuous tuning range near 960 nm. Assuming a 2 nm channel separation, this tunable VCSELs represents a tenfold increase in data transmission rates. However, there is no data available on the wavelength stability under severe vibration environments.

Tunable WDM filters are available but their response times are slower than is necessary for an agile transmitter or receiver. Lucent Technologies and Pirelli Cavi SpA (Milan, Italy) incorporate eight wavelengths, each delivering 2.4 Gbps data flow for an aggregate capacity of 20 Gbps over a single fiber. Ciena Corporation (Savage, MD) is delivering WDM gear incorporating 16 wavelengths for 40 Gbps (OC-48) of total capacity. Alcatel N.V., Hitachi Ltd., NEC Corp., ADC Telecommunications and Northern Telecom Ltd., have early single (future multiple) wavelength systems which can launch 10 Gbps onto a fiber. [47]

[47] Stevens et al. FAST report, Section 5-16

4.8.2.2.2 Quantum Well Mirror (QWM) VCSELS: Numerous attempts have been directed at creating a practical VCSEL semiconductor laser that can sustain simultaneously multiple frequency single mode operations. A unique approach based on the development of the QWM technology is currently being pursued at the Naval Air Warfare Center. The QWM is a multi-layered thin film semiconductor structure that has an effective plane of reflection. This effective plane of reflection exists within the structure (Figure 52).

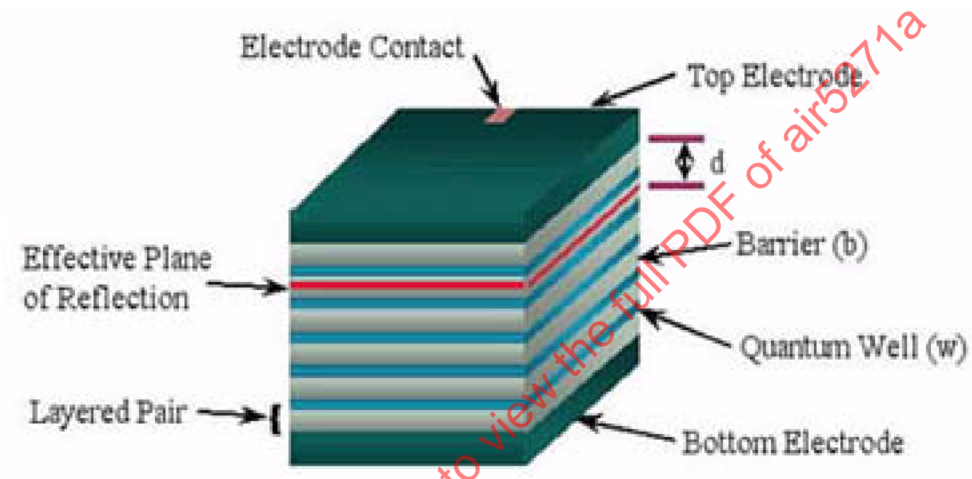


FIGURE 52 - A Single Quantum Well Mirror

Its position is a function of the reflectance at the interfaces between the layers and the thickness of the media that the light is traveling through before striking the interface. Because the position is a function of the reflectance, it is also a function of the index of refraction of the material. Any change in the index of refraction of the material causes a shift in the position of the effective plane of reflectance. Therefore, by using the quantum well structure with an applied electric field the quantum confined Stark effect will shift the index of refraction of the well material changing the position of the effective plane of reflection. This quantum well mirror concept is being utilized to eliminate mechanical dither in ring laser gyros.

This same device, a quantum well mirror can be used to change the optical, not the physical, cavity length in a VCSEL. If an array of these quantum well mirrors (Figure 53) are fabricated as a mirror for a VCSEL, each element within the array can be tuned to its own optical cavity length electronically by changing the bias voltage to the electrodes. Hence, each element within the array can be fixed at a specific optical wavelength or each elements can be tuned.[48]

[48] Karwacki et al. , GOMAC 2000

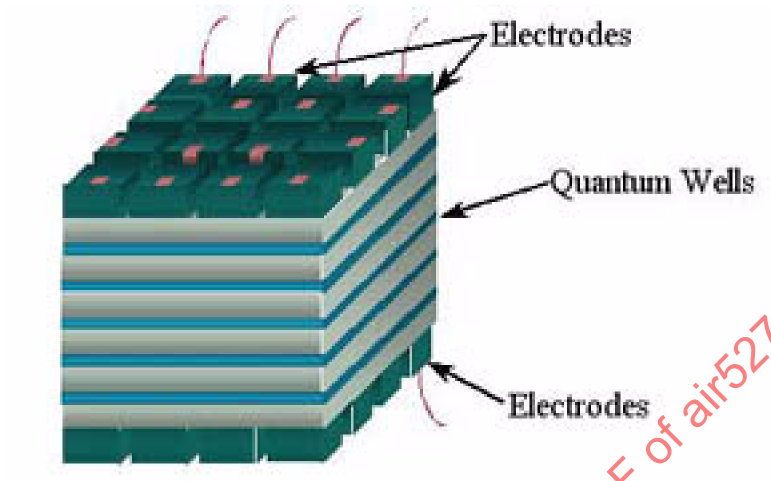


FIGURE 53 - A Multiple Quantum Well Array Mirror

4.8.3 Micro-Chip Lasers: Microchip lasers are small, compact, robust, high performance diode pumped solid state lasers that can be manufactured in high volume at low cost . A relatively low cost diode laser is used as an excitation source to pump a solid state laser "chip" of approximately 1 to 3 mm^3 in size to convert the poor spatial and spectral mode output of the diode laser into a spectrally pure, low noise beam at a longer wavelength. For typical Nd-doped laser materials such as YAG, the pump diode laser wavelength is ~809 nm while the most common output wavelengths are 1064 and 1319 nm. The improved output characteristics of the microchip laser allow numerous applications not possible with conventional edge emitting semiconductor lasers.

The microchip concept involves the use of semiconductor packaging technology. Simple microchip lasers are fabricated by polishing wafers of solid state gain material so they are flat and parallel and then coating them with dielectric mirrors. These wafers are subsequently cut apart using conventional semiconductor dicing techniques. Two dimensional arrays of microchip lasers are obtained by dicing wafers into larger squares and using two dimensional diode laser pump arrays. Microchip arrays have the advantage of lower production costs and nearly unlimited power scaling with constant brightness.

The microchip laser relies on the properties of materials such as Nd:YAG, as well as laser physics. For materials such as YAG, dn/dT (the change in index of refraction with temperature) is positive, and a thermally induced lens occurs from the heat generated by the pump laser beam. The thermal lens has the effect of stabilizing what would have been a marginally stable (flat-flat) resonator. This property produces a "auto-stabilized" resonator that conforms to the pump beam allowing for very simple fabrication and alignment during the manufacturing process.

4.8.3 (Continued):

The radius of the laser mode that is generated is generally larger then the radius of the pump beam; This leads to single transverse mode operation. An additional advantage of the auto-stabilized microchip laser mode is that the output laser beam always remains orthogonal to the planar output face of the microchip irrespective of the position or angle of the incident pump beam. This provides for simple pump alignment. Also, if the microchip laser beam is brought to a focus using a lens, the position of the focus is minimally changes for any motion between the pump beam and the microchip crystal. This property sets microchip lasers apart from other solid state laser cavities and provides for robust coupling of microchip lasers to optical fibers.

Commercial microchip lasers are presently being produced for cable TV applications with output coupling for cable TV applications with output powers of 200 mw CW in a single mode fiber at 1300 nm. Such power levels greatly exceed those of diode lasers presently used for similar applications. The relative intensity noise (RIN) of such a microchip laser is <-165 dB/Hz.[49]

Photonic sources for the fiber optic links require ancillary components for frequency modulation and wavelength selection - making them inherently large due to incorporation of these components. These sources also require powers greater than 100 milliwatts that operate in a single frequency regime. Future fiber optic links will continue to require high power but will additionally require low weight, environmentally stable photonic source packages for microwave and millimeter wave operation.

Two semiconductor-based laser technologies - diode-pumped solid state (DPSS) microchip lasers and Optically pumped semiconductor (OPS) - represent a new generation of "integrated diode lasers". These lasers combine the performance characteristics of diode-pumped solid-state lasers with cost effective, volume manufacturing techniques of semiconductor lasers. Coherent Inc., Santa Clara, CA, Micracor Inc., Acton, MA, and Uniphase Inc., San Jose, CA are manufacturing DPSS microchip lasers and OPS for the telecommunication market.

4.8.4 External Modulators: Modulators are currently the most commonly used integrated optical components. They function by controlling the amount of light transmitted into a fibre optic link from a continuous wave (CW) laser. The light transmitted through the modulator can be smoothly varied from zero to the maximum intensity.

4.8.4.1 Lithium Niobate Mach-Zender Interferometer Modulators: A Mach-Zehnder modulator comprises two-phase modulators and Y-junction splitters/combiners. A schematic of the modulator is shown in Figure 54. The operating principle is as follows: a voltage V(t) is applied to the central RF electrode. The optical signal is initially split into two equal portions at the 3 dB Y-junction. In accordance with the electro-optic effect the induced index change causes the phase of the optical signals to be advanced in one arm and retarded in the other. When the signals are re-combined in the Y-junction combiner, they are coupled into the single mode output guide if they are in phase, while if they are out of phase, they are transformed into a higher order mode and lost into the substrate.

49 Mooradian et al., pp. 17-19

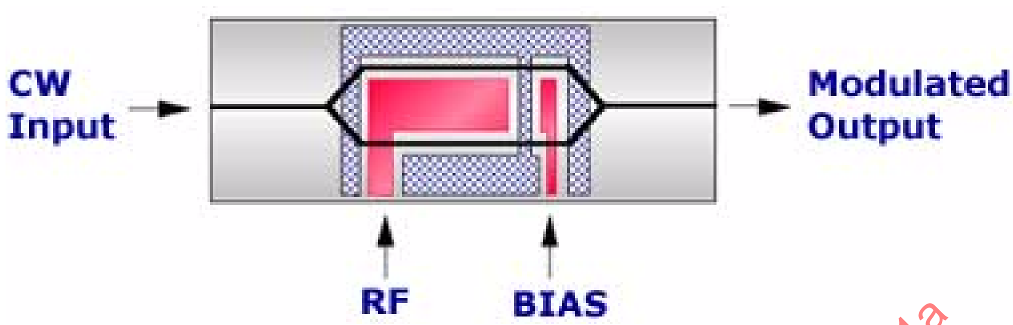


FIGURE 54 - Schematic of a Lithium Niobate Modulator Produced by IOC[50]

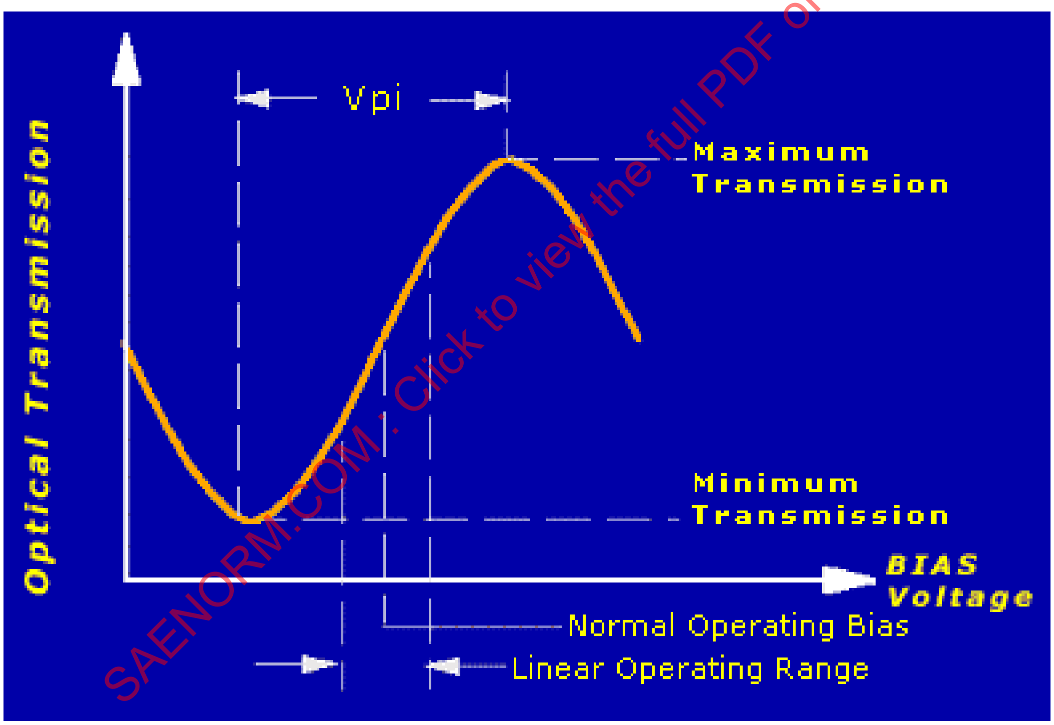


FIGURE 55 - Transfer Function of a Lithium Niobate Modulator

50 http://www.ioc.co.uk/products/appnotes.html

4.8.4.1 (Continued):

For phase differences between these two extremes only a portion of the light is coupled into the output waveguide. This gives rise to the characteristic co-sinusoidal transfer function in Figure 55. The major benefit of external modulation as compared to direct modulation techniques is the absence of frequency chirp. This is achieved through the use of a narrow line width CW laser source and the inherent characteristics of the external modulator.[51]

4.8.4.2 Quantum Well Solid State Modulators: When an electric field is applied perpendicular to the surface of a quantum well, the optical absorption of the quantum well can be changed. The important point about quantum well materials is that this change in absorption is relatively large permitting their use as efficient optical modulators. Modulators that work for light coming and out of the surface of a semiconductor chip are called "surface-normal" modulators. Usually with other semiconductor-based optical modulators, the changes in absorption are relatively weaker so the light has to come in and out of the edges of the chip and travel relatively long distances in semiconductor optical waveguides to get enough over-all change in optical transmission. A change in optical absorption with applied electric field or voltage is called "electro-absorption". The particular electro-absorption mechanism seen only in quantum wells is called the "quantum-confined Stark effect". This mechanism, like other electro-absorption mechanisms in semiconductors, is also very fast. There are no intrinsic speed limitations on the mechanism itself until time scales well below a pico-second. In practice, speed is limited only by the time taken to apply voltage to the quantum wells, which is typically limited by resistor-capacitance limits of the external circuit. Speeds of 40 GHz have been demonstrated.

The modulator works best typically at wavelengths of about 850 nm, in the near-infrared region of the spectrum. At this wavelength, the AlGaAs material is transparent, so there is no optical loss in the AlGaAs contact regions. GaAs itself is opaque at these wavelengths, so the substrate has to be removed to make a transmission modulator. Devices can be made with various other semiconductor materials for various operating wavelengths in the infrared region, and some devices have been demonstrated in the visible region.

In a typical surface-normal modulator, there will be about 50 to 100 quantum wells and will be a few microns thick. A typical device might have an operating voltage of 5 to 10 V, and the optical transmission of the modulator might change from 50 to 20% as the voltage was applied. Other ranges of transmission and voltage are possible with appropriate design of the device.[52]

[51] http://www.ioc.co.uk/products/appnotes.html

[52] http://www.bell-labs.com/project/oevlsi/tutorial/index.html

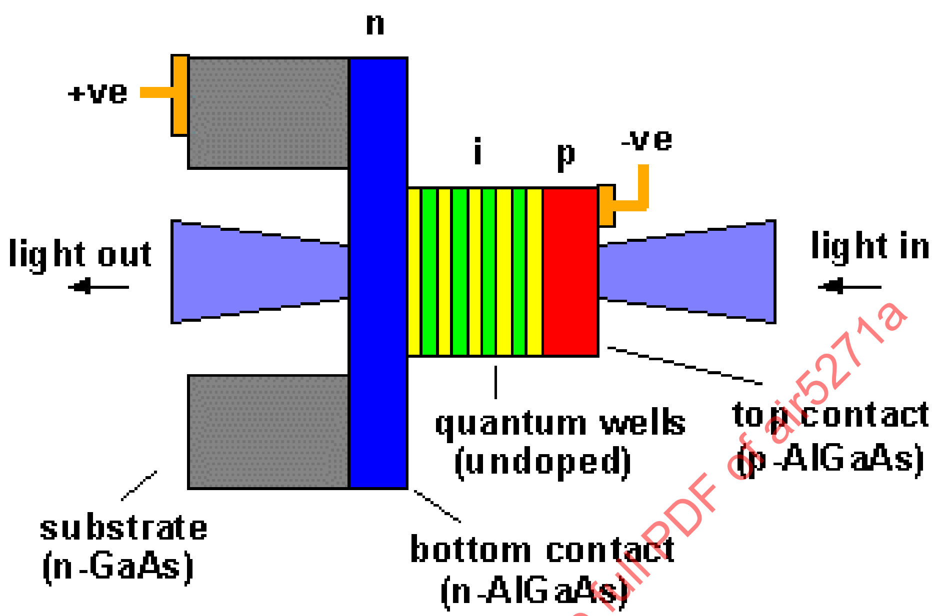
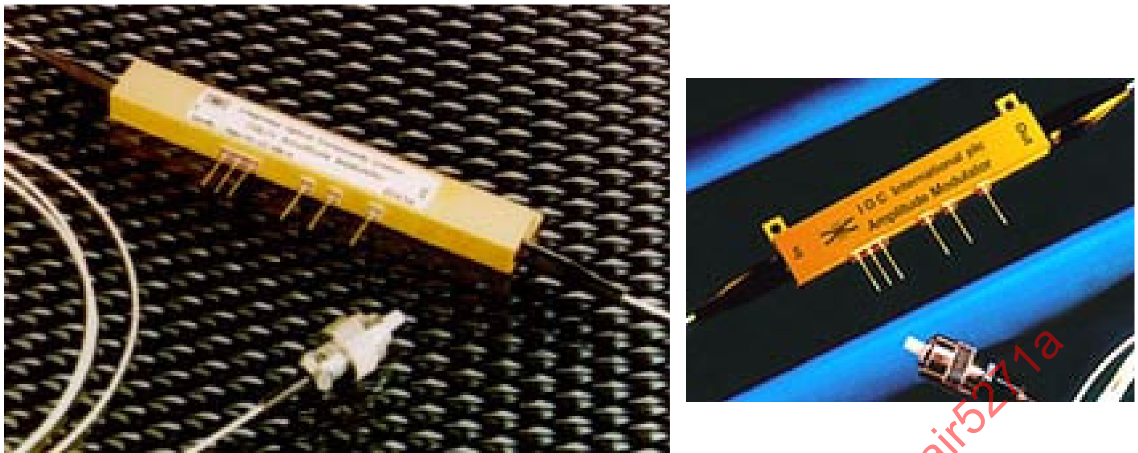


FIGURE 56 - Schematic of a Quantum Well Electro-Absorption Modulator[52]

4.8.4.3 External Modulator Availability: The most widely used external optical modulators are the Lithium Niobate Mach-Zehnder modulators (Figure 57) used with single-mode fibers. These devices are also capable of handling high optical powers (hundreds of mW) without damage. Operation up to 20 GHz was available years ago and 40 GHz performance is commercially available from various vendors. Two representative manufacturers are ANADIGICS of New Jersey, Uniphase Corporation in San Jose and IOC in the UK. This modulator design is composed of an optical waveguide, which splits into two interferometric arms. One of the arms has an electrical stripline positioned over it. The modulating signal is applied to this stripline. This waveguide stripline structure is constructed on a substrate of Electro Optic (EO) crystal and when the electrical signals are applied to the stripline the optical properties vary producing an interferometric response between the two arms at the point where they are re-combined into one waveguide. Optimum bias for modulation linearity is at a point situated at the mid-point of the maximum and minimum optical response. This point is designated the Vpi bias voltage. Symmetric two arm construction and the sinusoidal transfer function, result in very low second harmonic energy after initial phase error bias voltage adjustments.



(A) (B)

FIGURE 57 - Packaged Lithium Niobate Modulators (Courtesy (A) Uniphase[53] and (B) IOC[54])

4.8.4.4 Variations of External Optical Modulators Under Development: Subsequent development in external optical modulators has led to EO Polymer modulators ,which operate similar to EO crystals. These modulators have an electronic origin of the EO response, non-dispersive dielectric constants and very high mW operation (90 to 100 GHz). IPITEK Corporation Carlsbad, CA has devised a push-pull mode of operation using two electrodes with 180° difference between them. This method has reduced the electrical drive voltage by one half.

A unique asymmetrical design is being used by the Naval Research Laboratories where only one-half of the symmetric interferometer is constructed in Lithium Niobate. These devices utilize a mirror coating in the middle of each of the two arms causing the optical signal to be reflected back through the modulator, along with an open circuit electrical signal transmission line. Good RF performance and physically smaller modulators with lower drive voltages are achieved with half of the length of a conventional modulator to 40 GHz.

Ultra wideband modulators with high dynamic range are also reportedly being developed at the University of California Department of Electrical and Computer Engineering with Optivision, Inc. An optical fiber is closely coupled to a co-planer electrical waveguide that is in turn sandwiched between an electro-optic polymer layer and the fiber. 100 GHz is predicted for this technique.

4.8.4.5 Environmental Characteristics Of External Optical Modulators: The environmental ruggedness of Optical Modulators was tested by Uniphase Telecommunications products, Electro-Optics Group. The tests concluded that Lithium Niobate based modulators can be deployed (with proper design) in commercial, space qualified and military systems and will be qualified to Bellcore TR-NWT-000468 and MIL-STD-883 requirements.

53 http://www.uniphase.com/products/

54 http://www.ioc.co.uk/products/appnotes.html

4.8.4.5 (Continued):

The test that are being covered are: Accelerated Aging, Low Temperature Storage (-40 °C), Temperature cycling (-40 to +85 °C), Drop Shock (1500 grams), Fiber Pull (1000 grams), Damp Heat (humidity exposure), Thermal Shock Testing, Electro Static discharge (ESD), Vibration (Sine, 20 grams), Flammability, Solderability and Internal Water Vapor.

4.8.5 Modal Noise: The use of optical interconnects in aerospace systems will be limited by the maturity of the technology multi-mode fibers which are currently the medium of choice for military systems due to the availability of qualified parts. As the new family of lasers described above matures, the users of these devices must be aware of a potential source of errors in digital systems which occurs when lasers are utilized with multi-mode fibers: modal noise. Modal noise arises in any system in which a coherent source is used to excite a multi-mode waveguide interconnect in which one or more elements exhibit mode selective loss. The effect arises from variations in source properties during each bit, and therefore has significant components at the data rate, thereby precluding filtering as a means of eliminating its effect. The bit error rate for a digital link depends on the received signal-to-noise ratio at the decision point, thus if modal noise is sufficiently severe, the desired bit error rate may be unattainable. Even if the signal-to-noise ratio is better than required to obtain a specified bit error rate, the bit error rate may still be unacceptable since the modal noise combines with other noise mechanisms to determine the SNR at the decision point. In some situations, the addition of optical power can be used to compensate for modal noise, by increasing the received signal and hence improving the signal-to-noise for non data dependent noise sources. The magnitude of this power penalty increases as the signal-to-noise ratio due to modal noise decreases, becoming infinite at the point where the signal-to-noise ratio becomes equal to that required to achieve a specified bit error rate.

Modal noise is a form of partition noise. The total power launched into the waveguide system is constant, but is distributed in a time varying manner between some or all of the modes supported by the waveguide. Any component in the system, which can attenuate one mode preferentially over another, will give rise to amplitude modulation if the source or fiber characteristics change. If the fiber is completely undisturbed and the source always emits exactly the same wavelength of light, no modal noise will result. However, perturbations to the fiber will result in low frequency noise, while small variations in the source properties, temperature, or drive current will result in large changes in source parameters, This can occur as the source is modulated, possibly resulting in mode-hopping. The effect of modal noise is to degrade the signal-to-noise ratio at the receiver via generation of amplitude noise at frequencies comparable to those associated with the data transmission.

Modal noise and its effects are extremely complex, and are statistical rather than deterministic in nature. In designing a multi-mode optical link, it is important to accommodate modal noise, thus reliable but simple design tools are needed. Modal noise need not be a major problem in a multi-mode system used with coherent sources if the effect is considered in the design process.[55]

[55] Bristo et al., pp.189-191

4.9 Switching Mechanisms:

The use of optical interconnects for both networks and computer interconnects can dramatically improve avionics systems performance. A critical component to implement optical interconnects is a high speed switching mechanism. Switching is required for redundancy management in networks as well as a data routing mechanism for in computer architectures. Switching can be done in either the optical or electronic domain. For advanced optical backplanes, a trade must be made between high-speed serial or parallel transmission. Serial data transmission simplifies the switching but requires higher speed logic. Parallel transmission reduces latency by precluding the need for parallel to serial conversion and can utilize lower speed logic but requires multiple transmitters and receivers and very complex switches. Switching parameters which need to be optimized include: throughput, bandwidth, switching speed, power dissipation, packaging density, and fanout capability.

4.9.1 Smart Pixels: A new "hybrid" opto-electronic technology known as "smart pixel" technology has become the focus of considerable research worldwide. Smart pixels are generally defined as autonomous devices which process incident optical data, and then output the processed data in optical form, and the processing is generally done in the optical domain. There are currently four major lines of investigation of smart pixels: those based on multiple-quantum-well self electro-optic effect devices or (SEEDs), opto-electronic integrated circuits with detectors, transistors, and lasers or modulators in each pixel, vertical detector/emitter switches, and liquid crystal light valves integrated with silicon VLSI. In a sense, smart pixels represent the first major step in solving long standing connectivity problems confronting high performance interconnections and processing. Switching times for smart pixels are in the nanosecond and sub-nanosecond range. The reliability of these devices can be extremely high when implemented with state-of-the-art microcircuit technology and silicon since silicon PIN diode and microcircuit reliability is very predictive and has a well-documented reliability history in severe environments.

The advantages of using both optical and electronic technologies as hybrid systems becomes obvious as one further considers the strength of optical interconnects. In addition to higher bandwidth, which results from the non-interacting nature of optical beams, there is inherent parallelism available from optics resulting in higher bandwidth interconnects and packing densities than electrical interconnects. In such parallel architectures, it may be desirable that the interconnection array has the capability of both fan-in and-fan-out. Here, fan-out is the delivery of one pixel to the output of several other pixels and fan-in is the reception of the output of the output of several pixels at one pixel input. The delivery of signals for fan-out and fan-in is easily implemented in optics (i.e. Couplers and/or beam splitter/combiner optics) although both fan-in and fan-out typically require pixels that have gain. For this reason, optoelectronic integrated circuits (OEIC's) with gain are typically superior in performance to circuits in which the circuits are purely optical or electrical.[56,57]

56 Stevens et al., FAST final report pp. 5-27, 5-28

57 Lightwave Magazine website, August, 1999.

4.9.2 Electro-Mechanical Switching: Most commercial switches utilized for redundancy management utilize an electro-mechanical element, such as a spring loaded galvanometer mirror, to deflect the optical signal from one fiber into another once power is lost. These electro-mechanical approaches use magnetic or piezoelectric drivers to physically move a fiber to align it with different output fiber ports. Most of these devices have very slow response times (on the order of milliseconds) causing considerable loss of data during the switching process. The loss of data increases as the data rate increases and a gigabit per second network would lose a million bits of information during a one millisecond switching period. Electro-mechanical switches are also rather bulky, expensive and environmentally sensitive making them very impractical for aircraft use. Since they are mechanical in nature, they can pose major reliability concerns operating in an aerospace environment subject to temperature and pressure extremes, shock, and vibration. Rather ingenious low-mass spring activated silicon substrate mirror designs that appear to be rather rugged are being tested but the risk in the selection of these devices remains high since limited flight test data is available.

A new family of micro-electromechanical systems (MEMS) devices, which are tiny movable micromachines mounted on integrated circuits, are now found in products ranging from airbags to tunable lasers. This technology is now being applied to switching. The basic idea is to use relatively standard silicon processing to make small moving mirrors which can be used to deflect light. These devices are now used in digital projectors. The mirrors designed to be about 300 microns in diameter are flipped or raised by an electrostatic attraction or actuator. AT&T uses standard integrated circuit design techniques that fabricate 64 free-rotating hinged micro-mirrors, together with thin mechanical actuators, on a 1 cm square silicon chip that is about one fourth the size of a postage stamp. The actuators trigger the micro-mirrors to rapidly flip up and down, directing light beams into optical fibers.

4.9.3 All Optical Switching: Optical domain switches have been prototyped which utilize beam steering caused by various optical phenomena and non-linear effects in solid materials. These include electro-optic switches, magneto-optic switches, acousto-optic switches, photo-refractive devices, holographic and photo-lithographically defined diffraction gratings, polarization rotation switches, and liquid crystal switches. The most successful of these technologies utilizes non-linear effects in Lithium Niobate crystals. Optical signals are injected into Y-branched waveguide couplers fabricated in the material and voltages applied across electrodes deposited on the material surface cause the nonlinear effect which causes the light to transfer from one output arm of the coupler to the other. Most of these devices are designed for use with single mode fibers and laser light sources. Devices of this type are typically temperature sensitive, lossy, rather inefficient, and/or expensive. Temperature compensation can be utilized to produce useful devices for aerospace applications. Because of the cost, speed, weight and volume limitations of optical switching, this capability is only provided in a small percentage of commercial LAN terminals, which specify multi-mode fiber technology. The devices have been employed in long-haul communications and increased commercial use can lead to reduced cost.[58]

58 Stevens et al., FAST Final Report pp. 5-27 and 5-28

5. OPTICAL AMPLIFIERS:

The telecommunications industry has incorporated optical amplifiers into their long haul transmission systems. These devices provide a means of obtaining signal gain in an optical transmission media. The gain is used to overcome the fiber attenuation of the glass fiber which accumulates over long transmission lengths. Prior to the availability of this device, repeaters were used for regeneration, reshaping, and re-timing of the transmitted signals. Since these repeaters required the conversion of the optical signal to an electronic format and re-conversion to an optical format for re-transmission, each repeater was designed for a specific data format and transmission rate. These repeaters, are signal bandwidth sensitive due to the electro-optical interface, are expensive and inflexible as channel capacity is upgraded. Optical amplifiers have become the ideal candidates for replacing these repeaters. They provide longer hops between stations and transparency to bit rate and transport protocol, both important in cost control.

There are two main types of optical amplifiers (1) doped fiber amplifiers (DFAs) and (2) semiconductor optical amplifiers (SOAs). In both cases, the objective is to increase the repeater spacing for a system that is limited by fiber attenuation.

5.1 Erbium-Doped Fiber Amplifier (EDFA):

An optical fiber amplifier is essentially a single-pass laser cavity where stimulated emission is used to increase the gain of all optical signals passing through the cavity. An optical fiber, properly doped with a suitable rare-earth serves as the optical cavity. Since the amplifier is a single-pass device, high power pump diodes must be used to excite the erbium ions in the fiber. Various coupling schemes to optimize gain have been devised and these devices are available in reasonable size packages. Connectorized glass rods can also be used with fiber optic connectors provided for the signal and pump diodes. Optical amplifier technology has added a new dimension to the design and performance of modern optical based communication networks. The performance characteristics and design considerations involved with EDFAs include amplifier optical gain and linearity along with noise figure and gain spectra.

Optical amplifiers augment the wavelength capacity of optical fibers, allowing wavelength division multiplexing (WDM) as a practical form of increasing channel capacity without installing new fiber lines or upgrading the transmission bit rate. For example, a 2.5 Gbits/sec signal may use up to 10 GHz of bandwidth, corresponding to about 0.1 nm at 1550 nm. Assuming that channels are spaced 1 nm apart, and that the amplifier's bandwidth is 40 nm, the implementation of dense wavelength division multiplexing (DWDM) may result in a 40-fold increase in capacity. DWDM systems of 4, 8, and 16 channels employing EDFAs at both their transmitter and receiver sides are currently implemented in LANs, terrestrial and undersea links. Prototypes are underway for 32, 64, 128, channels hyper DWDM system.

5.1 (Continued):

The main elements of the EDFA are the Erbium-doped fiber and pump laser diode. This type of amplifier is fabricated using a length of conventional single-mode silica fiber, doped with a rare earth metal such as Erbium (Er). A concentration of about 100 ppm is adequate to provide high gain. If a Laser Diode is coupled into the fiber, it acts as a pump to increase the energy (signal level) of an incoming signal as it travels along the fiber. The pump light excites the Er to higher levels causing the signal power to gradually increase as the signal travels along the fiber.

Pump laser sources are commercially available at both 980 and 1480 nm. The 980 nm pump is available with a fiber Bragg gating to stabilize the laser output. Placing the grating inside the hermetically sealed butterfly package protects it from environmental and mechanical stress.

There are several tradeoffs between using a 980 or 1480 nm pump laser in an EDFA. The 980 nm laser chip has high quantum efficiency. To achieve 100 mW output a 980 nm laser module may take 225 mA of current, while the same power output from a 1480 nm module requires over 400 mA of drive current. Another advantage of the 980 nm module is its lower noise. The absorption and emission curves of the fiber overlap in the 1480 to 1550 nm region. Therefore, light from the 1480 laser that is not absorbed may be amplified as noise. Because the 980 nm module pumps at a wavelength that is 500 nm shorter, noise is not created by unabsorbed pump light.

Optical amplifiers are designed to operate with specific conditions such as amplifier's gain, output power, and noise figure. The most significant application of EDFAs is an amplifier in direct detection lightwave communication systems. Three classes of role dependent amplifiers are the receiver preamplifier, the in-line amplifier, and the power (booster) amplifier. The receiver preamplifier is used before detectors to enhance the signal-to-noise (SNR) of a direct detection system without having to rely on complex and often expensive detection techniques such as coherent detection. This improvement in BER at the receiver improves power budgets. Pre-amps also act as limiting amplifiers. The in-line amplifier is used to compensate for signal power degradation due to distribution splitting losses and fiber attenuation. It is used to replace regenerators and repeaters without the need for signal reconditioning. The power amplifier is used after the transmitter laser to boost the transmitted power to a level not available from the laser. It is typically bi-directionally pumped with high power pump laser diodes.

The noise figure (NF) is the ratio of the input to the output signal-to-noise ratio of the amplifier. It is related to the spectral intensity of the forward propagating amplified spontaneous emission (ASE) as well as to the amplifier gain. The main contributors to the noise figure are signal shot noise and ASE-signal beat noise. Optical power of current power amplifiers can exceed 16 dBm (or 40 mW), which is useful for long repeaterless links or for branching in CATV, fiber-to-the-home delivery, and analog communication systems.

5.1 (Continued):

Most standard EDFAs are constructed using several discrete components, including a pump laser diode packaged in a butterfly or TO package, a fused biconical WDM coupler, a fiber pigtailed isolator, a large size beam splitter, and a packaged photodetector. Extra insertion loss not only decreases the EDFA gain but also degrades the noise figure. By applying combined fiber grating technology for pump laser diode stabilization, planar beam splitting for signal monitoring, and using laser diode and photodetector chips for size reduction, all the EDFA components can be integrated in a single, standard butterfly package

5.2 Semiconductor Optical Amplifiers (SOA):

A laser diode used as a light source is simply an amplifier with enough positive feedback to cause oscillation. Making reflective facets at each end of the semiconductor chip provides this feedback. So by removing the feedback using facets with anti-reflective coatings, the laser oscillator can be converted to an optical amplifier.

Two types of semiconductor amplifiers can be made, depending upon the reflectivity of the coatings on each facet. First, when the facet reflectivities are lower than for a laser oscillator, but still allow some light to be reflected back into the active region, the amplifier is called a Resonant or Fabry-Perot amplifier. Second, if the facet reflectivities are very low, a single pass amplifies light entering the device, and the amplifier is called traveling wave amplifier. In practice, even with the best anti-reflective coating, there is a small amount of facet reflectivity. This means that most semiconductor amplifiers operate somewhere between a Fabry-Perot and traveling wave amplifier; gain values in the 25 to 30 dB range are readily achievable, with an output power in excess of 5 dBm. The single pass gain is different for polarization modes, implying that polarization controlling devices may be necessary for this type of amplifier.

5.3 Comparison of SOA and EDFA Performance:

Standard components for the terrestrial communication industry are normally rated for 0 to 65 °C, but may operate outside this range. Extended temperature range of -55 to + 95 °C should be achievable. One potential problem with a SOA is crosstalk between wavelengths. This is generally more serious with SOAs than with EDFAs. Here a modulated signal at one wavelength influences the population inversion, and thus is seen as a gain change at another wavelength. The crosstalk phenomena depend on the spontaneous emission lifetime from the high-energy to low-energy state. If the lifetime is large enough compared to the rate of fluctuations of power at the input signals, the electrons cannot make the transition from the high-energy state to the lower energy state in response to these fluctuations. The lifetime of the excited state of EDFAs is about 10 ms and about 1 ns for SOAs. Thus EDFAs are usually better than SOAs for WDM applications.

5.3 (Continued):

A typical high-grade semiconductor amplifier provides a gain of at least 12 dB over a 40 nm bandwidth for a gain bandwidth product of 630 nm. Typical NF in this case is 10 dB. The high-gain region for a typical EDFA lies between 1525 and 1565 nm. Gain can vary 5 to 7 dB over this region, with a sharp peak at 1530 nm, when no special means are employed to flatten the gain spectrally. The gain variation can be made considerably flatter using in-line filtering devices such as Bragg gratings and interference filters or by reducing the pumping level below full inversion. A price is paid in this case in terms of reduced average gain and increased NF, which may be acceptable in many applications including DWDM. Without any gain flattening enhancements, the gain in an EDFA at full inversion and hence optimum NF approaching 3 dB (with the normal passive components, this is increased to around 5 dB) is quite flat over the range 1540 to 1560 nm. In this case, 25 to 27 DWDM channels at the ITU wavelengths can be carried, with a small-signal gain of around 30 dB (110 mW, 980 nm pump) depending on fiber type, thus giving a gain – BW product of 20,000 nm.[59]

6. AIRCRAFT INSTALLATION:

High density optical interconnects permit the utilization of new installation techniques never utilized in Generation I optical interconnects. The commercial industry is exploring these methods which may be adapted for aerospace utilization.

6.1 Conduit Enclosed Cables:

Conduits are generally used on aircraft for one of three reasons.

1. Protecting cable from an unusually harsh environment.
2. Guiding cable through a difficult installation area.
3. Guiding long, unbroken cables through spliced aircraft segments.

Of these reasons, the last two are similar in that they involve use of conduit to guide and support a cable rather than protect it from an environmental condition. The difference between the two is that in reason two, the guided region is short in comparison with the total length of the cable, and in reason 3 the total guided length is a major fraction of the total cable length. In practice, reasons 1 and 2 are often applicable to small (tactical) aircraft, and reasons 2 and 3 are often applicable to large (transport) aircraft.

For installations in which the conduit is used for environmental protection of the cable or for guiding the cable through difficult installation areas, the cable used is normally a cable intended for stand-alone (unprotected) use because the conduit is normally shorter than the cable. A second reason for using stand-alone cable in a conduit in these applications is that it is generally desirable to minimize the number of different types of cable used on an aircraft. If stand-alone cable is used in most locations of an aircraft, it will generally be used in conduit where conduit is required. Cable of this type will be discussed in the next section.

59 Stevens et al., FAST Final Report pp. 5-25 to 5-27

6.1 (Continued):

Cable for conduit may be of two types: cable that requires the conduit for protection, guidance, and support; and cable that only requires guidance and support. However, the differences between them are smaller than might be expected. These differences are mostly confined to the outer jacketing, as both require a similar fiber for similar applications, both require a buffer between the fiber and strength members, and both require strength members to allow them to be pulled into the conduit.

Cable for long, unbroken conduit installation is different from stand-alone cable in that long sections of the cable will of necessity be pulled for installation. That is as opposed to present practice for stand-alone cable in which the cable is normally laid in place, and only pulled through short, difficult areas. Therefore, the cable requires substantial longitudinal strength, and a slippery outer surface is desirable. Such cable also requires considerable resistance to fluid chemical attack, because should an undesirable fluid get inside the conduit, the cable could be exposed for a considerable length of time.

Other characteristics of the environment for cable for conduit include the following:

- Long term temperature exposure will be similar to that for stand-alone cable, but short term thermal excursions will be reduced by the presence of the conduit. Also, the possibility exists of forcing a temperature controlling fluid through the conduit.
- The vibration and shock environments will be the same as for other cable, however the cable design can make use of the fact that the cable will be constrained in a conduit rather than clamped at discrete locations.
- Bend, twist, and crush tolerance requirements will be similar to those for other cables to meet conditions encountered during cable installation and maintenance. An added bend requirement will be derived for installations such as landing gear and wing folds; however, there the limitation will be the conduit. The cable, relying on the conduit for support can be very thin and flexible, and so tolerant of considerable bending.

An example of a cable for conduit installation is an 18 fiber ribbon cable produced by W. L. Gore and Associates for transport aircraft use. The cable uses the same graded index, polyimide buffered 100 µm/140 µm/170 µm fiber used elsewhere in aircraft. The fibers are wrapped individually, and the bundle is wrapped as a whole in GoreTex™ material and the entire structure is sintered into a compact ribbon. The ribbon is then surrounded by a strength member which is overcoated with the outer jacket material. The resulting cable relies on the conduit only for support and guidance. It has the longitudinal strength, chemical resistance, fire resistance, and environmental tolerance of the single fiber cables now used in aircraft.

6.2 Stand Alone Cable:

Stand alone cable is installed without conduit except in those regions were conduit is helpful for guiding the cable during installation, or protects the cable from an unusual environmental hazard, such as wind buffeting.

6.2 (Continued):

Stand-alone cable can be single fiber cable or multiple fiber ribbon cable. Past experience has shown that single fiber cables run alone in aircraft are vulnerable to mechanical damage, especially during maintenance on other systems. It seems to be best to run optical fibers in a ribbon cable, bundle single fiber cables together into a harness, or run the single fiber cables with other cables. Burying single fiber cables in electrical wire bundles protects them from maintenance actions, but is risky in that the optical fibers must be buried deeply within the cable and great care must be taken with how the optical fibers branch out from the cable. Burial of the optical fibers in an electrical cable also exposes the optical fibers to the heat generated by the electrical cable.

Any single fiber cable used in aircraft must be robust enough to survive installation and use in the aircraft. That means that each fiber requires a buffer, strength member, and jacket. In addition, aircraft experience has shown that a buffer coating of polyimide on the glass greatly extends the life of the fiber and it tolerates well the aircraft environment, which the common acrylate buffers do not.

Two types of single fiber cables have been successfully developed for aircraft use, loose tube construction cables, and tight tube construction cables. Both types exceed the aircraft environmental requirements, but they vary in the details of their environmental performance. For that reason, both will be retained as available for use, with the appropriate cable to be chosen for each situation. Ribbon cables for aircraft also require a level of robustness which exceeds that available in common telecommunication ribbon cables. However, each fiber does not need a strength member and jacket, only the entire cable. This allows for a lighter weight and lower cost per fiber than with harnesses assembled of many single fiber cables.

6.3 Air Blown Fiber (ABF):

Air Blown Fiber (ABF) is a new optical fiber installation technique being used commercially for local area networks which utilizes either compressed air or dry nitrogen to blow light thin fibers into a previously installed tube. This method has several advantages over standard methods of "pulling" fiber. First, the fiber optic unit is blown into vacant tubes thereby greatly reducing fatigue. Splice free fiber can be installed with this method for up to 1.9 km with a near zero tensile stress. This method provides the ability to blow out fiber optic cables and reinstall them. Air blown fiber installation uses single fibers or fiber optic ribbons.

The following are features and benefits of air blown fiber:

- Addition, removal, or replacement of fibers anytime.
- Far fewer splices are required.
- Push-fit connectors make it quick and easy to re-route vacant inner tubes, and blow fiber into the resulting new pathways.
- Fiber can be “blown out” as easily as you blow it in.

6.3 (Continued):

Either way, there's near zero tensile stress on the fibers. Blown fiber technology was invented by British Telecommunications™ PLC and developed and manufactured by Sumitomo Electric Industries. These fibers are blown into tubes that are extremely rugged – ideal for harsh, outdoor environments where air blown fiber is used. The LAP (Laminated Aluminum Polyethylene) jacket is designed to prohibit water invasion into the cable. The steel strength member can handle up to 1000 pounds pulling tension. The seven tube (no central strength member), steel armored, doubled jacketed, LAP cable is designed for direct burial applications (Figure 58).[60] This installation technique has not been utilized to date in military platforms and issues of reliable operation in a high vibration or shock environment remain to be investigated.

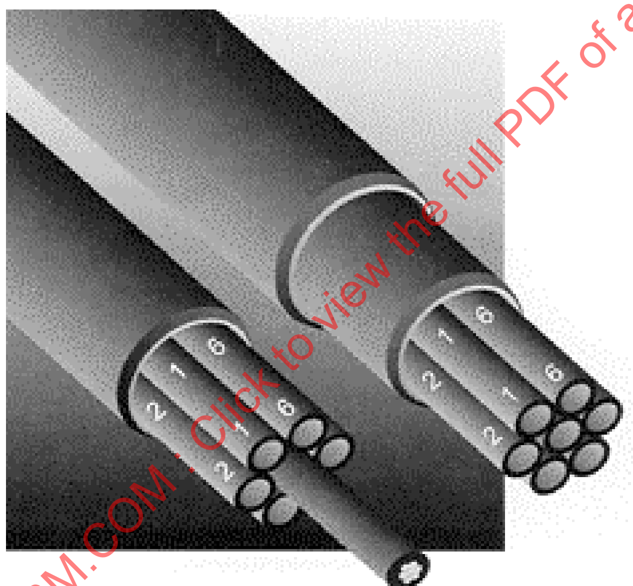


FIGURE 58 - Lap Sheath Tube Cables By Sumitomo Corp

6.4 Splicing:

Splicing of ribbon cable can utilize silicon V-groove technology Similar to that utilized in ribbon connectors. Figure 59 shows an isometric view of one version of a multi-fiber positioner (MFP). This MFP has a glass cover bonded permanently to an anisotropically etched silicon base. The anisotropic etching of the silicon provides the required fiber positioning V-grooves and lead-in chamfer “funnels”. The cover includes a hole that provides access to a portion of each V- groove through the cover. MFPs with different outside dimensions can be designed and constructed in the version developed for the splice, the overall dimensions were 10 millimeters long by 4.4 millimeters wide by 1.3 millimeters thick. The base is fabricated using a silicon wafer. The cover is fabricated using a glass wafer; clear glass covers provide the benefit of allowing visual inspection of the V-groove channels.

60 http://www.sel-rtp.com/products/abf/lapshth.html

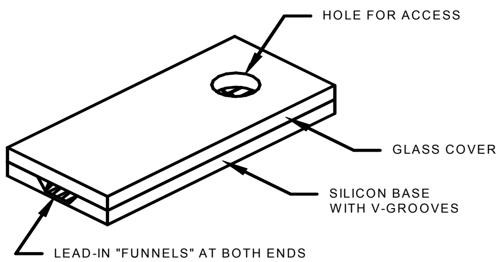


FIGURE 59 - Isometric View of MFP Used in Splice Case

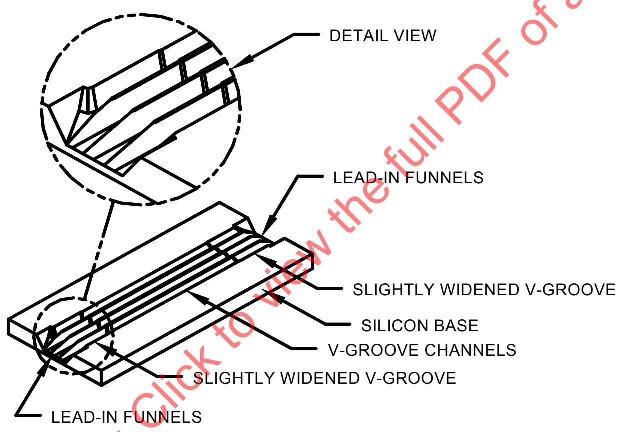


FIGURE 60 - Isometric View of the Silicon Base With the Cover Cut Away

6.4 (Continued):

Figure 60 provides an isometric view of the silicon base with the cover cut away. This figure exposes a clearer view of the features that are etched into the silicon. As shown, this silicon has four V-groove channels that locate and position the optical fibers. These V-grooves are sized for 170 micron fibers. Portions of these V-grooves have been slightly widened to facilitate the insertion of the optical fibers into the V-grooves (with cover attached). In addition, the V-grooves have been provided with lead-in chamfers at their initial entrances. These lead-in chamfers facilitate hand threading of optical fibers by providing "funnels" to get each fiber started into its channel. To provide a clearer view of the funnels and chamfered “step-down” in the V-groove width, an enlarged detail view is provided. With minor modifications in the design, more or fewer channels can be provided. With modified designs, the V-groove channels can be created with different widths to accommodate either smaller or larger diameter fibers.

6.4 (Continued):

The MFPs have been produced using micro-machining techniques adapted from the semiconductor industry. The MFPs were fabricated from two separate wafers that were processed independently, then bonded and finally diced into multiple components similar to the MFP shown in Figure 62. This production technique provides strong and stand-alone structures with very tight tolerances while promising economical parts at moderate volumes.

Via micro-machining, silicon wafers were etched to create triangular shaped V-grooves. The starting material was a single crystal silicon wafer with (100) orientation and a (110) flat. Using photolithographic techniques, very precise patterns were created in photoresist materials on the surface of the silicon wafer. The photoresist material was processed to create a very precise etching mask on the silicon surface. To create V-grooves, this mask contained open parallel bands that were parallel to the (110) flat. Certain etching solutions have the ability to preferentially etch one crystallographic plane much faster than the others. When subjected to these etching solutions, the open bands had material removed from the (100) plane to create a groove whose sidewalls were (111) planes. Because these (111) planes etch at a much slower rate, a trapezoidal groove was created. By allowing the etching to continue, the (100) plane disappears to create a triangular shaped V-groove with (111) planes as sidewalls. The resulting angle between the (111) plane and the (100) plane was 54.7 degrees. As discussed earlier, these grooves with these angles formed precise channels to hold and position the optical fibers. The glass wafer was processed to cut holes through the entire thickness. Following processing, the two wafers were bonded together. Then the bonded structure was diced to provide many MFPs.

Again, it must be emphasized that the cover is permanently bonded to the silicon base before the optical fiber is inserted. The creation of a one-piece multiple fiber positioner that can receive fibers into triangular openings is an important aspect of this development. Prior work placed optical fibers into longitudinal grooves in silicon (or other material) and then placed a separate cover over the assembly. With prior methods, the termination of optical fibers was sufficiently difficult to require laboratory conditions and essentially to preclude field termination of cables. The MFP of the current development overcomes these earlier difficulties. Now, the optical fibers can be slid into the funnels at the end of the MFP and pushed through the full length of the V-groove in the MFP. This operation has proven to be sufficiently easy to allow for insertion by unaided hands with unaided vision.

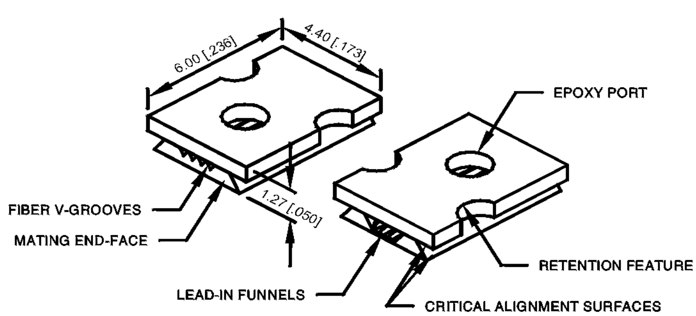


FIGURE 61 - Provides Isometric Views of Both Ends of an MFP Customized for Use in a Connector

6.4 (Continued):

The outside sizes and shapes of MFPs can be customized to facilitate their use in different applications. For example, for use in a splice, the MFP shown in Figure 61 would be very desirable because it has lead-in funnels at both ends and because the exterior is very “box-like”. On the other hand, for use in separable connectors, different exterior shapes are more desirable. Figure 61 shows an MFP customized for use within separable connectors. This connector MFP has lead-in funnels at only one end of the MFP and the connector MFP also includes other features to improve its utility as a connector building block.

The cover has a through hole and two retention notches. The optical fiber is inserted from the end that includes lead-in funnels. The mating end face does not have lead-in funnels; rather, the V-grooves extend all the way to the surface to provide optimum alignment for the fibers. The two retention notches are designed to help secure the MFP within each half of the separable connector as the connector halves are repeatedly mated and separated. In this connector MFP, the cover extends beyond the base to create critical alignment surfaces to help align mating pairs of MFPs with separable connectors. These critical alignment surfaces are created on the silicon base by the same anisotropic etching process used to create the fiber V-grooves; however these surfaces are allowed to etch through the entire thickness of the silicon wafer. The critical alignment surfaces on the cover are simply the flat underside of the cover. The overall dimensions of the MFP shown in Figure 61 were 6 millimeters long by 4.4 millimeters wide by 1.3 millimeters thick. Discussion of the use of connector MFPs will follow later.

After insertion, the optical fibers are positioned by two etched surfaces in the silicon and by the flat surface of the permanently attached cover. Figure 62 provides a cross-sectional view of the optical fibers after insertion into an MFP. This illustration shows four fibers located in the triangular V-grooves created by the permanently attached cover and the silicon base. More specifically, each fiber is positioned by two etched surfaces on the silicon, and by the flat inside surface of the cover. The fiber resides completely within the V-groove provided by the silicon. None of the fiber protrudes beyond the joining plane into the cover. This is markedly different and superior to many of the prior practices where grooves were provided on both sides of the “joining plane”. With the current method, the alignment of the cover is dramatically less critical; lateral misalignments of the cover relative to the base do not adversely affect the positioning of the fibers in the V-grooves. If desired, the fibers can be permanently bonded within the MFP by inserting epoxy or other adhesives into the corner regions around each fiber. In practice, it has proven to be convenient to introduce epoxy by the use of a pipette or syringe using the hole shown in Figure 61.

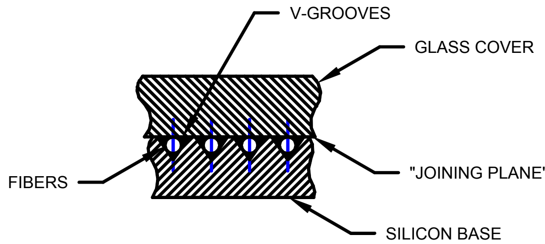


FIGURE 62 - Cross-Sectional View of the Optical Fibers After Insertion Into an MFP

6.4 (Continued):

The MFP shown in Figures 60 and 61 was used to create a 4-channel splice for use with a ribbon cable carrying four polyimide buffered optical fibers. The MFP was mounted on a flexible polymeric “elevator” and housed within a protective metal shell. The splice and shell design were developed to facilitate user-friendly operation. The shell assembly included a novel method for cable attachment. This splice design should allow practicable field use in adverse conditions.

Figure 63 presents an exploded isometric view of the mechanical splice assembly showing its components. The overall mechanical splice assembly consists of two halves: an upper splice case and a lower splice case. To facilitate user-friendly operation, all the required elements for the total splice would be attached to one of these halves; no additional loose pieces would be required for the splice. The overall splice assembly satisfies a number of requirements, including housing the MFP that provides the alignment means for the mating optical fibers, securing the cables, providing mechanical support and providing environmental protection. The overall design also attempts to simplify the operations required for splice installation in the field.

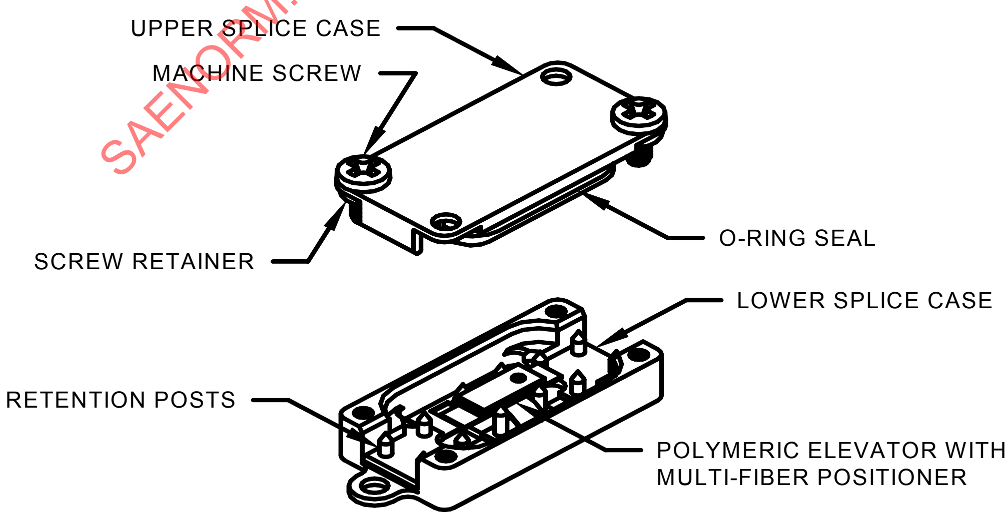


FIGURE 63 - Exploded Isometric View of Mechanical Splice Assembly

6.4 (Continued):

The lower splice case provides the following functions. It holds the flexible polymeric film “elevator” that supports the MFP. It provides cable retention posts that penetrate locating holes along the sides of the ribbon cable to both locate and lock the cable within the splice case body. It provides surfaces for an O-ring seal to provide environmental protection. It provides a cable-pulling eyelet to help with cable installation.

The upper splice case provides the following functions. It supports an O-ring to provide the seal for environmental protection. It carries retained screws for mechanical connection to the lower splice case. It captures the tops of the cable retention posts to provide additional cable retention strength. It completes the metal shell around the splice for mechanical and environmental protection.

The first step in the proposed mechanical splice procedure is the preparation of both cables at their mating ends. An appropriate length of cable jacket and reinforcement material would be removed from each cable to expose the individual optical fibers with their polyimide buffers intact. Each of the four optical fibers would be cleaved to provide a good optical end-face surface at the appropriate distance from the cable locating holes.

Second, one cable would be mounted to the lower splice case. All four fibers from one cable are slid into one end of the MFP. Following fiber insertion, the cable is secured by pressing it into the lower splice case so that the cable retention posts enter the locating holes along the sides of the cable. Figure 64 shows a top view of the optical ribbon cables in the lower splice case.

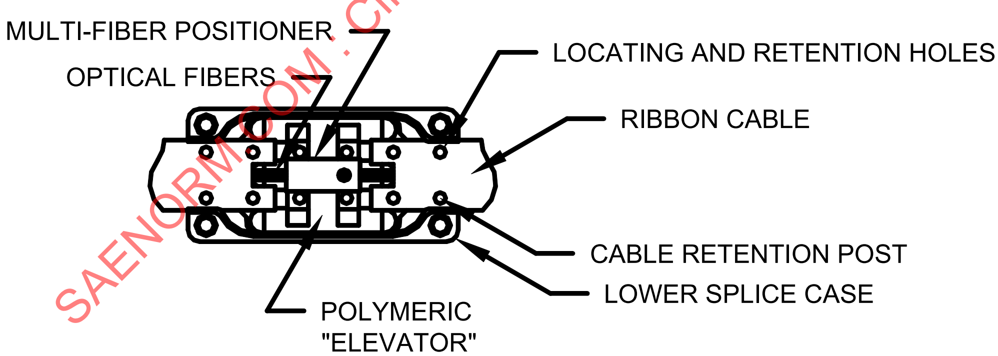


FIGURE 64 - Top View of the Optical Ribbon Cables in the Lower Splice Case

Third, the mating cable is mounted to the lower splice case in a similar fashion. All four fibers are slid into the opposite end of the MFP. Again, the cable is secured by pressing it into the lower splice case so that the cable retention posts enter the locating holes along the sides of the cable.

6.4 (Continued):

Finally, the upper splice case is attached and secured by tightening the machine screws until tight. Once tightened, the O-ring provides a complete environmental seal with face seals against the tops of the fiber optic ribbon cables and lateral seals along the case side walls. When assembled, the overall dimensions of the splice case were 37.7 millimeters (42.2 millimeters to the end of the cable pulling eyelet) long by 19 millimeters wide by 8.5 millimeters (10.5 millimeters to the top of the screw head) high.[61]

6.5 Branching and Fan-Out Techniques:

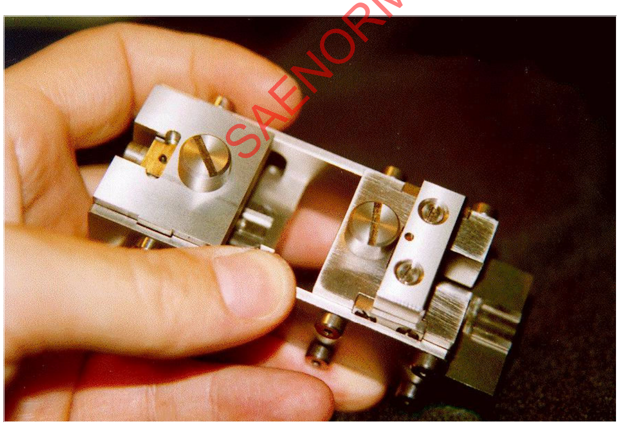
The use of suitable splice cases and tree and star microchip couplers can provide an efficient and compact method of branching and fanout from a ribbon cable. Silicon bench and molded substrate technology can be used to make such assemblies rugged and cost effective.

6.6 Fasteners or Tie-Down Techniques:

Ribbon cables lent themselves to low cost tie-downs because of the flat nature of the cable. The Fasteners and Tie-Down "Straps" must be designed so that micro-bend losses are not induced in the fiber optic ribbon cable. One can envision such low cost and light weight materials as VELCRO© to fasten the light weight cables to the airframe. Suitable attachment methods should also be provided for the couplers, splice cases, branching elements and cable-to-cable connectors.

6.7 Installation and Repair Tools:

Suitable low cost portable installation and repair tools such as cable strippers, fiber cleavers, and fiber polishers are being developed for fiber ribbon cables for aerospace environment. Below in Figure 65 are photographs of a stripper and cleaver being developed at Boeing, Long Beach, CA.



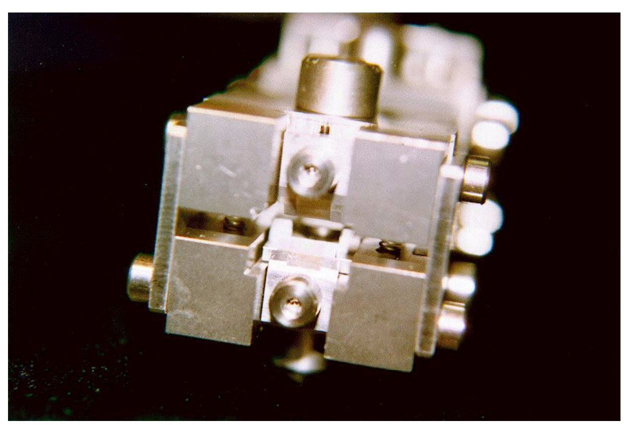


FIGURE 65 - A Handtool for Batch Stripping and Cleaving of Optical Fibers in a Ribbon Cable (Courtesy Boeing Corp., Longbeach, CA)

61 Sellers, SPIE, pp. 31-42

7. TIME DIVISION MULTIPLEXED NETWORK TOPOLOGIES:

The topology of a network refers to the physical routing required to interconnect the terminals in a network. The most common topologies proposed for implementation of fiber optic time division multiplexed LANs are the linear, star, ring and mesh topologies. Cost, reliability, maintainability, and the operational environment must also be factored into the equation for the network design and component selection.

7.1 Linear Topology:

The linear topology, which utilizes "tee" couplers, is shown in Figure 66 and has certain characteristics. This topology uses couplers, which can provide high reliability to tap optical energy from a linear array of terminals. The number of terminals is limited by the optical power, which can be coupled into the fiber, as well as by the fiber size and attenuation, by connector, splices and "tee" coupler losses. Wide dynamic range receivers must be utilized to accommodate the linear power drop down the fiber if identical receivers are to be utilized at each network node.

Couplers, which can be tailored to couple variable amounts of light in proportion to the position along the length of the linear bus, and automatic gain control (AGC) can be employed to balance the system. These techniques are not a preferred approach for standardized networks

The linear power drop down the fiber if identical receivers are to be utilized at each network node. Couplers, which can be tailored to couple variable amounts of light in proportion to the position along the length of the linear bus, and automatic gain control (AGC) can be employed to balance the system. These techniques are not a preferred approach for standardized networks with broadly differing installation lengths where component interchangeability and low cost are essential. The reliability advantage gained by utilizing passive couplers is offset by the high output required from the source to accommodate a large number of terminals. The use of active couplers can jeopardize network reliability since a failure can impact all downstream terminals. If active couplers are utilized, an adequate bypass mechanism must be employed to circumvent the failed active coupler.

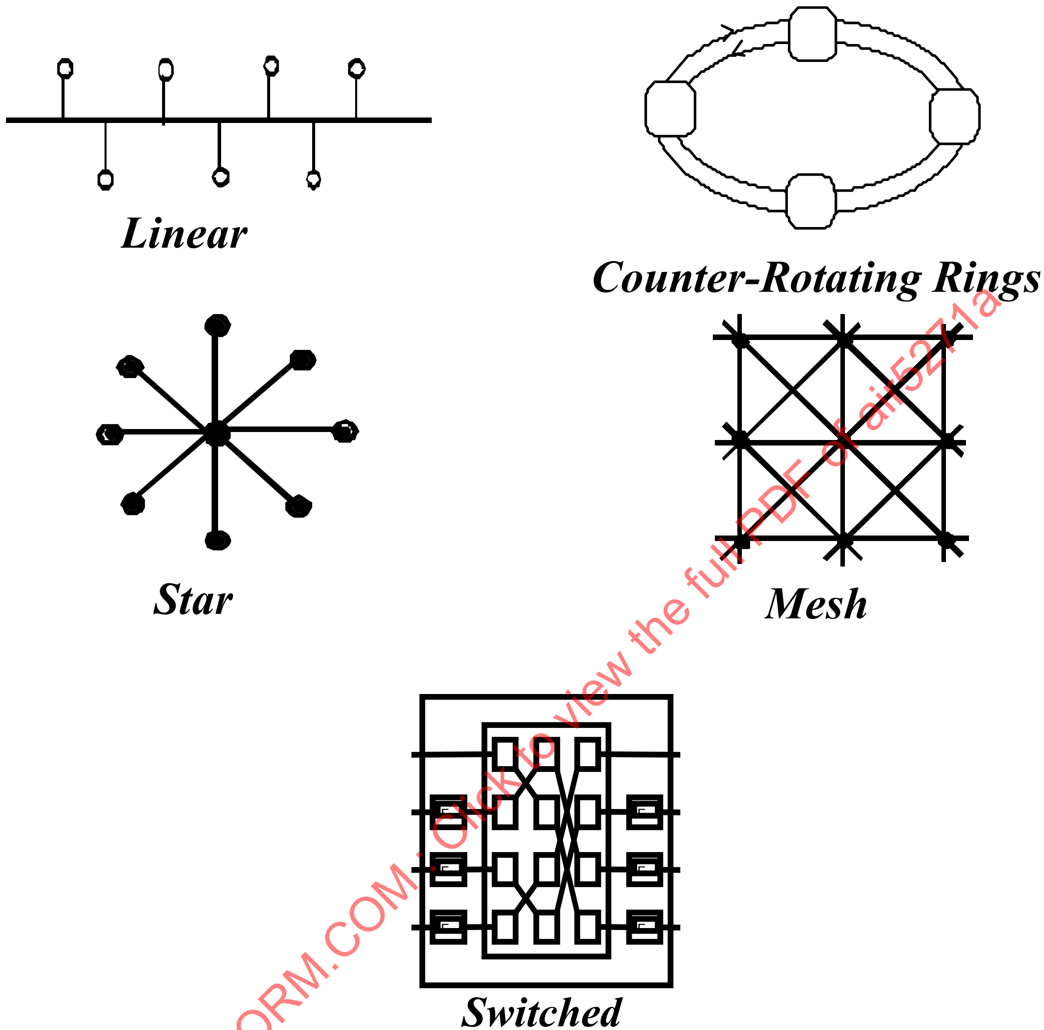


FIGURE 66 - Common Network Topologies

7.2 Star Topology:

Figure 66 shows a star coupled topology for networks. In this topology, optical power is divided equally among a number of terminals through the utilization of a transmissive or reflective star coupler. A loss budget calculation must be performed to determine the number of terminals, which can be implemented for a star topology in harsh environments with provision for connectors, splices and adequate safety margin. If more terminals are required than can be accommodated by the passive star, then an active star must be utilized to provide gain. The star topology requires that all fibers be brought to a central distribution/power division node. This topology does not lend itself easily to expansion after installation in an aircraft. If the fiber lengths or the number of connectors in each fiber are not equal for all terminals, receiver dynamic range and sensitivity become design issues. Also since light from any terminal must reach all terminals, the sources must be driven at an output level sufficient to accommodate receiver sensitivity and dynamic range without impacting source reliability. Operation over large temperature extremes (i.e. 55 to +80 °C) can affect the output level of the optical source so suitable junction temperatures should be maintained to assure good reliability. A power failure for an active star coupler can prove catastrophic to all network nodes. Fault tolerance can achieved by total redundancy in all components of the system including power supplies or battery backup. Mil-STD-1773 is usually implemented with a star topology.

7.3 Ring Topology:

The Ring network topology shown in Figure 68 utilizes an optical source and detector at each terminal in the ring. These devices act as a repeater by detecting and regenerating the optical signal for data passing through the terminal. They also serve as the means to extract optical data for use by the terminal or for sending information generated by a given terminal to the next adjacent terminal. If one examines this topology, it quickly becomes evident that the entire network consists of a series of point-to-point links. Thus a major element in the power budget equation budget, the coupler loss, is eliminated. This arrangement permits the use of low sensitivity and low dynamic range receivers since only the next adjacent terminal must be accessed. This permits the use of reliable low power sources, low sensitivity and dynamic range receivers. This topology is ideal for a network with a large number of terminals and can be easily expanded. The margin built into this design can be utilized to good advantage in adverse environments such as aerospace and automotive applications.

7.3 (Continued):

While providing the advantages listed above, the point-to-point nature of this topology can pose reliability concerns since a single point failure in either the optical, electronic, or power supply elements can cause a failure in the entire ring. The use of counter-rotating rings is typically utilized to prevent a total failure of the ring in case of a single point failure. This loopback technique can only tolerate two failures before the sub-rings become isolated preventing sharing of data between all remaining terminals. Redundant hardware (transmitters, receivers, fibers, power supplies) and/or a bypass device are required to obtain fault tolerance. Electro-mechanical bypass switches are slow (on the order of milliseconds) which can cause significant loss of data at high data rates and may be inadequate for severe environments (especially vibration and shock). Lithium Niobate electro-optic switches can switch very rapidly but the loss (typically several dB/cm) must be taken into consideration and have a limited operating range. These devices are single mode devices requiring single mode sources, fibers and connectors. The use of repeaters at each node adds to the total time delay of the network so latency effects must be taken into consideration in the network design. The data rate of the ring, and the repeater logic speeds can bound the repeater delays and total network latency. Ring networks provide growth potential through higher speed operation and ease of node insertion into the ring.

7.4 Mesh Topology:

The mesh topology provides for redundant data paths between nodes so that data can be reconfigured around a failed terminals or interconnections. These networks are used where the ultimate in reliability and redundancy is desired. Usually these networks require some means of monitoring the data paths and a switching mechanism to circumvent faults. These networks are relatively expensive due to the need for redundant hardware.

7.5 Switched Topology :

In packet switched (i.e. time division multiplexed) network, the channel bandwidth is divided into time slots or packets and messages are sent as a series of packets and re-assembled at the destination node. Circuit switched architectures eliminate the need to share the channel bandwidth after the connectivity is established. Electronic cross bar switches provide a means of connecting any input going into the switch to any output. These are available but are rather costly when they must operate at high data rates compatible with optical data transmission. In-band control is a very difficult problem as data rates increase where the header must be decoded and the data routed in real-time. Electronic switching also requires optical-to-electronic conversion entering the switch and electronic-to-optical conversion circuitry leaving the switch, which greatly increases cost. Optical switching requires single mode waveguide technology but can operate as the very high optical transmission rates. Devices with a high number of input/output channels are not currently available but research is being actively pursued as mentioned above. High speed electronic crossbar switches are the near term solution with switched photo-diode array (i.e. Smart pixel) approaches also being pursued. These devices can be used with both single and multi-mode fiber and waveguides. Much research is ongoing for all-optical crossbar switches using electro-optic waveguide switches, optical amplifier gain control, self electro-optic effect devices, smart pixels or active waveguide technology. Most optical switching devices and optical amplifiers are single mode, which can easily be coupled to single mode fiber waveguides.